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Experimental Evaluation of New Rotary Instruments with Innovative Manufacturing Treatments Potentially Affecting Clinical Performance. Part 1: Flexibility

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Abstract

The mechanical behavior of nickel-titanium (NiTi) rotary instruments is strongly influenced by alloy composition, manufacturing processes, heat treatments, instrument geometry, and taper. Flexibility is considered one of the most important properties of modern endodontic instruments because it determines the ability of files to follow the original root canal anatomy while minimizing procedural errors. This study aimed to evaluate and compare the influence of instrument design, taper, and innovative manufacturing treatments on the flexibility of small-sized NiTi rotary instruments. Three groups of NiTi instruments designed for the preparation of narrow canals were evaluated: ZARC Slim Shaper 15/.04 (Simit Dental, Italy) and Onyx 15/.03 and 15/.04 (Edge Endo, USA). Ten instruments from each group were tested using a custom-made bending device. Flexibility was assessed at four different locations along the instrument (3, 5, 8, and 20 mm from the tip) using a 45° bending angle. Mean bending resistance and standard deviation values were calculated. Statistical analysis was performed using one-way ANOVA to identify differences among groups. ZARC 15/.04 showed the highest bending resistance at all measurement points, indicating lower flexibility compared with ONYX instruments. The difference increased progressively from the apical to the coronal portion of the instruments. ONYX 15/.03 demonstrated the lowest bending resistance, particularly at 3 mm from the tip. Increasing taper from .03 to .04 significantly increased instrument rigidity. ANOVA analysis showed highly significant differences among groups at all tested distances ($p < 0.05$). Instrument flexibility is strongly influenced by taper, design, and manufacturing treatments. Evaluating flexibility at multiple locations along the instrument provides additional information compared with conventional single-point bending tests.

Keywords: nickel-titanium instruments; flexibility; heat treatment; taper; bending resistance; root canal preparation; rotary instrumentation.

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Introduction

In recent decades, technology has improved significantly in the field of endodontics [1-4], even if the biggest innovations concerned mainly rotary and reciprocating instrumentation [5-9]. The introduction of nickel-titanium (NiTi) alloys has increased the simplicity, rapidity, and predictability of mechanical root canal preparation. Compared with stainless-steel instruments, NiTi rotary instruments exhibit superior flexibility, allowing them to negotiate curved canals while reducing the risk of procedural errors such as canal transportation, ledging, apical zipping, and perforation. However, the clinical performance of NiTi instruments depends on several interacting factors, including alloy characteristics, thermal treatment, cross-sectional design, taper, and manufacturing procedures [10-15].

Among these mechanical properties, flexibility plays a fundamental role because it determines the ability of an instrument to adapt to the original anatomy of the root canal system [16-18]. Highly flexible instruments generate lower restoring forces during canal negotiation, reducing lateral pressure against dentinal walls and improving canal-centering ability. In addition, improved flexibility contributes to a more favorable distribution of tensile and compressive stresses during rotation, which may enhance resistance to cyclic fatigue and reduce the risk of intracanal instrument separation.

The mechanical properties of NiTi alloys can be modified through thermal processing. Heat treatments alter the phase transformation behavior of the alloy, increasing the proportion of martensitic and R-phase structures at clinical temperatures and reducing the elastic restoring forces typical of conventional austenitic NiTi instruments. These modifications have led to the development of instruments with improved flexibility while maintaining adequate cutting efficiency and torsional resistance [19-25].

Nevertheless, flexibility is not determined exclusively by metallurgical characteristics. Instrument geometry, including taper, cross-sectional area, flute design, and the amount of metallic mass, has a major influence on bending resistance and other mechanical properties. Increasing taper results in greater metal volume along the instrument length, which increases rigidity and may reduce the ability of the instrument to follow complex canal curvatures.

A limitation of previous flexibility assessments is that standard tests evaluate bending resistance only at 3 mm from the instrument tip, according to ISO 3630-1 [26]. Although this area represents a clinically important region because it is frequently subjected to severe curvature and stress, flexibility varies considerably along the length of an instrument, since curvature can also be present in the coronal and middle parts of canals. Evaluating multiple points provides a more comprehensive understanding of the mechanical behavior of rotary instruments during clinical use. This need has become more relevant in recent years due to the introduction of new manufacturing processes aiming at changing the flexibility of the instruments in different portions. The selected instruments for this study, ZARC Slim Shaper (Simit Dental, Italy) and Onyx (Edge Endo, USA), are examples of this new trend, even if the goal is reached with different innovative methodologies (coating vs selective heat treatment).

The purpose of this study was therefore to evaluate the influence of taper, instrument design, and innovative manufacturing treatments on the flexibility of small-diameter NiTi rotary instruments intended for narrow and curved canals. ZARC 15/.04 instruments were compared with ONYX instruments with equivalent tip sizes but different tapers (15/.04 and 15/.03) to determine whether and how design and manufacturing characteristics affect bending resistance along the entire working portion of the instrument.

Materials and Methods

Three groups of nickel-titanium rotary instruments were included in this study: ZARC Slim Shaper 15/.04, ONYX 15/.04, and ONYX 15/.03. A power analysis was performed to determine the required sample size. Based on the expected differences in bending resistance, ten instruments from each group were selected for mechanical testing. The selected instruments have been designed for the preparation of narrow and anatomically complex root canals. Although the instruments shared a similar apical diameter (#15), they differed in taper, design characteristics, and manufacturing treatment. Therefore, the objective of the comparison was not to establish the superiority of one system over another, but to evaluate how differences in geometry and manufacturing processes influence the flexibility profile of NiTi instruments.

Flexibility measurements were performed using a custom-designed testing device composed of a stainless-steel platform equipped with: a calibrated load cell connected to a digital display, a movable positioning system allowing standardized placement of the instrument, and an analog goniometer for accurate control of the bending angle. (Figure 1)

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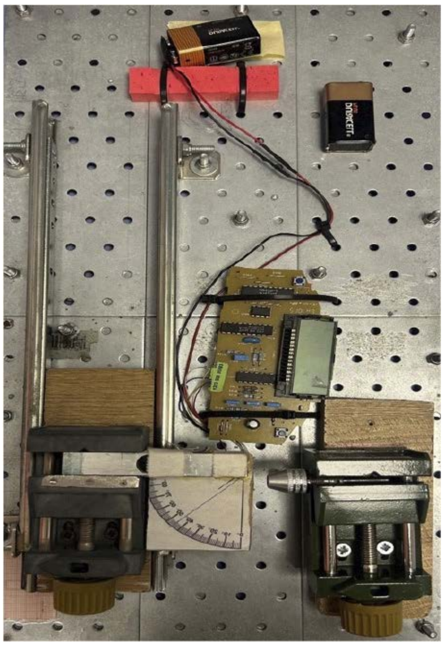
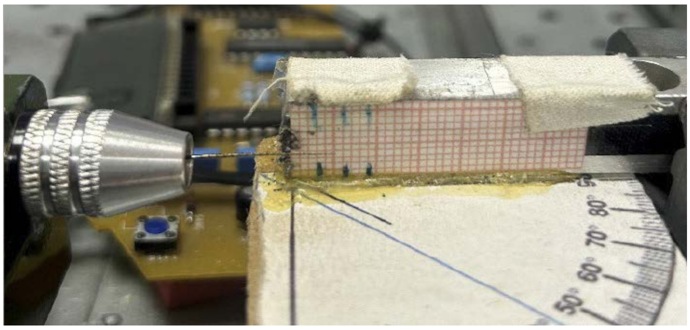


This system allowed reproducible measurement of bending resistance at different points along the instrument length. Each instrument was positioned horizontally and subjected to a 45° bending angle (Figure 2). Flexibility was evaluated at four different distances from the instrument tip: D3= 3 mm from the tip; D5= 5 mm from the tip; D8= 8 mm from the tip; D20= 20 mm from the tip. All measurements were recorded in g/cm.



For each group, mean bending resistance values and standard deviations were calculated for all tested locations. Because more than two independent groups were compared, statistical analysis was performed using one-way analysis of variance (ANOVA). This statistical approach was selected to evaluate whether significant differences existed among the three instrument groups while controlling the risk of Type I error associated with multiple comparisons. The significance level was established at $p < 0.05$.

Results

The complete results are presented in Tables 1-4. Tables 1-3 report the individual bending resistance values obtained for the ten instruments tested in each group at the four measurement locations (D3, D5, D8, and D20). Table 4 presents the one-way ANOVA results comparing the flexibility of ZARC 15/.04, ONYX 15/.04, and ONYX 15/.03 instruments at each distance from the tip. All measurements are calculated in g/cm: the lower the value, the more flexible the instrument.

Overall, the results demonstrated clear differences in mechanical behavior among the three groups. The ZARC 15/.04 instruments exhibited the highest bending resistance at all measurement locations (Table 1), indicating the lowest flexibility within the tested groups. At 3 mm from the tip, ZARC 15/.04 showed a mean bending resistance of 45.33, whereas ONYX instruments demonstrated (Tables 2-3) considerably lower values, confirming superior apical flexibility. The difference between groups increased progressively toward the coronal portion of the instruments. At 20 mm, ZARC 15/.04 reached a mean bending resistance value of 1152.08, exceeding twice the value observed for the second most rigid instrument, ONYX 15/.04.

The comparison between the two ONYX instruments demonstrated the influence of taper on flexibility. ONYX 15/.04 consistently showed higher bending resistance compared with ONYX 15/.03.At 3 mm, ONYX 15/.04 showed a mean resistance of 33.88, while ONYX 15/.03 demonstrated a value of 13.30. A similar trend was observed at 8 mm, where ONYX 15/.04 reached 96.13, compared with 40.90 for ONYX 15/.03. These findings indicate that increasing taper from .03 to .04 significantly increases instrument rigidity due to the greater accumulation of metallic mass along the working portion.

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Table 1. Stiffness Test for Zarc 15/.04. All values in g/cm.

Sample	3mm	5mm	8mm	20mm
1	38	115	257	1155
2	41	85	175	1197
3	44	83	225	1155
4	48	54	120	1215
5	37	62	213	1165
6	42	59	258	1211
7	53	79	220	1342
8	42	75	162	1020
9	57	57	259	1350
10	52	65	292	1067
Mean Value	45,4	73,4	218,1	1187,7
sd	6,769211344	18,39202726	52,64651513	103,7465394

Table 2. Stiffness Test for ONYX 15/.04. All values in g/cm.

Sample	3mm	5mm	8mm	20mm
1	23	55	88	231
2	16	26	59	313
3	11	16	56	325
4	15	24	58	157
5	21	27	78	204
6	18	56	61	153
7	15	25	52	178
8	15	17	67	297
9	17	33	52	146
10	17	31	63	223
Mean Value	16,77777778	31	63,44444444	222,6666667
sd	3,359894178	13,95229969	11,54892972	67,99844769

Table 3. Stiffness Test for ONYX 15/.03. All values in g/cm.

Sample	3mm	5mm	8mm	20mm
1	17	24	48	166
2	24	29	38	155
3	13	32	44	244
4	15	37	47	207
5	9	24	38	189
6	4	39	36	172
7	15	42	34	187
8	7	27	49	238
9	10	43	48	146
10	19	20	27	149
Mean Value	13,3	31,7	40,9	185,3
sd	4,949747468	13,43502884	0	14,14213562

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The ANOVA analysis demonstrated (Table 4) statistically significant differences among the three groups at every measurement location. All values were highly significant, confirming that the different instrument designs and manufacturing approaches produced distinct mechanical behaviors throughout the entire length of the instruments.

Table 4. Comparison between different instruments.

Distance	(ANOVA)	P value	Significance
3 mm	Zarc vs i-Files	5,45x10-12	Statistically significant
5 mm	Zarc vs i-Files	4,94x10-9	Statistically significant
8 mm	Zarc vs i-Files	6,81x10-12	Statistically significant
20 mm	Zarc vs i-Files	1,48x10-23	Statistically significant

Discussion

The mechanical performance of NiTi rotary instruments is determined by a complex interaction between alloy properties, heat-treatment protocols, instrument geometry, and manufacturing processes [21,24]. Among these characteristics, flexibility represents one of the most clinically relevant properties because it directly affects the ability of an instrument to maintain the original root canal anatomy during shaping procedures. [16-18].

A flexible instrument can negotiate curved canals while generating lower restoring forces against the canal walls [10]. This reduces the tendency of the instrument to straighten inside curved anatomy, thereby decreasing the risk of undesirable procedural errors such as canal transportation, ledge formation, apical zipping, and perforation. Furthermore, lower bending resistance allows a more homogeneous distribution of mechanical stresses during rotation, potentially improving resistance to cyclic fatigue and reducing the probability of instrument separation.

The ability to measure bending resistance at multiple locations represents an important advantage compared with conventional flexibility tests, which generally evaluate mechanical behavior only at 3 mm from the tip [16]. Since root canals present complex three-dimensional curvatures and different stress distributions along their length, a multipoint evaluation provides a more complete characterization of instrument behavior. The present study evaluated flexibility at four different locations along the instrument (3, 5, 8, and 20 mm from the tip). This approach provides additional information compared with conventional bending tests performed only at 3 mm, as described by ISO 3630-1 [25]. Although the apical 3 mm represents a critical region because it frequently negotiates the most curved portion of the canal, the mechanical behavior of an instrument changes progressively along its length due to variations in diameter, taper, and metallic mass. Therefore, a multipoint evaluation provides a more realistic representation of instrument behavior during clinical use.

The ANOVA analysis confirmed highly significant differences among the tested groups at every measurement location. At 3 mm from the tip, the extremely low p-value ($p = 2.10 \times 10^{-11}$) confirmed that ONYX instruments were significantly more flexible than ZARC 15/.04. Similar highly significant differences were observed at 5 mm ($p = 9.8 \times 10^{-10}$), 8 mm ($p = 2.63 \times 10^{-12}$), and 20 mm ($p = 5.69 \times 10^{-23}$). These results indicate that the differences between the tested systems are not limited to the apical region but extend throughout the entire instrument length. The statistical findings support the conclusion that variations in taper, design, and manufacturing treatment produce measurable differences in mechanical performance.

When analyzing the influence of instrument design and manufacturing treatment, at 3 mm from the tip, ZARC showed a mean bending resistance of 45.33, while ONYX instruments demonstrated considerably lower values. The difference became progressively greater toward the coronal portion of the instruments. At 20 mm from the tip, ZARC reached a mean bending resistance of 1152.08, exceeding twice the value observed for ONYX 15/.04. This behavior suggests that the ZARC design provides a greater structural rigidity along the instrument body, which may be associated with a larger metallic core, differences in cross-sectional geometry, or a manufacturing process aimed at improving torsional strength and structural stability.

Increased rigidity may provide some advantages, including improved torque transmission and greater resistance to torsional deformation. However, excessive stiffness may negatively affect the ability of an instrument to follow complex canal curvatures [24]. A rigid instrument tends to generate higher lateral forces against dentinal walls, potentially increasing the risk of canal transportation and unnecessary removal of sound dentin.

In contrast, the ONYX instruments showed lower bending resistance, indicating a more flexible mechanical behavior. The combination of optimized geometry and heat treatment may contribute to a more favorable phase composition of the NiTi alloy, increasing the presence of martensitic structures and reducing the elastic restoring forces typical of conventional austenitic NiTi instruments.

Heat treatment has become one of the most important developments in NiTi instrument technology because it allows manufac-

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turers to modify transformation temperatures and tailor mechanical properties according to clinical requirements. Heat-treated instruments generally exhibit improved flexibility and fatigue resistance while maintaining adequate cutting efficiency and torsional performance [15,23].

The comparison between ONYX 15/.04 and ONYX 15/.03 clearly demonstrated the significant influence of taper on instrument stiffness. Although both instruments had the same tip diameter (#15), the 15/.04 instrument showed considerably greater bending resistance than the 15/.03 instrument at all measurement locations. At 3 mm from the tip, ONYX 15/.04 showed a resistance value of 33.88 compared with 13.30 for ONYX 15/.03. At 8 mm, the difference became even more evident, with values of 96.13 and 40.90, respectively.

These findings confirm the well-established relationship between taper and flexibility. Taper determines the rate at which the instrument diameter increases from the tip toward the shaft. A .04 taper instrument increases in diameter by 0.04 mm for each millimeter of length, resulting in a greater accumulation of metallic mass compared with a .03 taper instrument.

Because bending stiffness is strongly influenced by the cross-sectional area and moment of inertia of the instrument, even small increases in taper can produce substantial reductions in flexibility. This effect becomes particularly evident in the middle and coronal thirds, where the increase in diameter produces a progressive increase in rigidity.

From a clinical perspective, smaller tapers may provide advantages in narrow and curved canals because they allow better preservation of canal anatomy and reduce the risk of transportation. Conversely, larger tapers may improve shaping efficiency and irrigation dynamics by creating a wider canal preparation, but this benefit is achieved with increased structural rigidity.

Overall, the results of the present study highlight the importance of flexibility as a fundamental characteristic of modern endodontic instruments. The apical third of the canal frequently presents the greatest curvature and anatomical challenges. Instruments with increased apical flexibility can follow these curvatures more effectively, reducing the tendency to straighten and preserving the original canal trajectory.

Preservation of the original canal anatomy is essential for successful endodontic treatment because excessive dentin removal may weaken the tooth structure and increase the risk of complications. Flexible instruments also reduce mechanical stress concentration during rotation, which may contribute to improved cyclic fatigue resistance.

However, flexibility should not be considered an isolated mechanical objective. An excessively flexible instrument may compromise cutting efficiency or torque transmission. Therefore, modern instrument development aims to achieve an optimal balance between flexibility, torsional resistance, and cutting ability. The results of this study demonstrate that this balance can be modified through both metallurgical and geometric approaches. While heat treatment can significantly improve alloy flexibility, taper remains a major determinant of bending resistance because of its effect on metallic mass.

A limitation of the present study is that flexibility measurements were performed at room temperature. The mechanical behavior of heat-treated NiTi alloys is influenced by temperature because phase transformation characteristics determine the relative proportions of martensitic and austenitic phases. Since intracanal temperatures are approximately 35-37°C, the flexibility values observed under laboratory conditions may differ slightly during clinical use.

In addition, this investigation evaluated bending resistance only. Other clinically relevant properties, such as torsional resistance, cutting efficiency, debris removal, and cyclic fatigue resistance, should also be considered when evaluating overall instrument performance.

Conclusions

The present investigation compared ZARC 15/.04 instruments with ONYX instruments in sizes 15/.04 and 15/.03. These instruments were not identical in design or manufacturing philosophy; therefore, the aim was not to determine whether one system was clinically superior, but rather to evaluate how differences in taper, heat treatment, and manufacturing approach influence flexibility.

Within the limitations of this study, the results demonstrate that both geometric and metallurgical factors strongly influence instrument flexibility. Taper represents a major determinant of bending resistance because increasing metallic mass significantly increases instrument rigidity. Heat-treatment strategies and manufacturing approaches can further modify NiTi mechanical properties, allowing manufacturers to develop instruments with different flexibility profiles.

Evaluating flexibility at multiple locations along the instrument provides a more comprehensive understanding of mechanical behavior than conventional single-point testing. It may contribute to better characterization of modern NiTi rotary systems.

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Figure legends

Figure 1. Custom-designed device used to measure bending resistance of nickel-titanium rotary instruments.

Figure 2. Instrument positioned in the testing device during 45° bending-resistance measurement.

Table legends

Table 1. Individual bending-resistance values for ZARC Slim Shaper 15/.04 measured at D3, D5, D8, and D20 (unit as reported in the source file: g/cm; unit requires author confirmation).

Table 2. Individual bending-resistance values for ONYX 15/.04 measured at D3, D5, D8, and D20 (unit as reported in the source file: g/cm; unit requires author confirmation).

Table 3. Individual bending-resistance values for ONYX 15/.03 measured at D3, D5, D8, and D20 (unit as reported in the source file: g/cm; unit requires author confirmation).

Table 4. One-way ANOVA comparing bending resistance among ZARC Slim Shaper 15/.04, ONYX 15/.04, and ONYX 15/.03 at D3, D5, D8, and D20. [AUTHOR QUERY: regenerate from the validated source dataset; the current embedded table contains an inconsistent group label and p-values.]

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