

Comparative Buckling Strength and Metallurgical Analysis of Five Classic NiTi Endodontic Rotary Files

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ABSTRACT

Objective: Nickel-titanium (NiTi) rotary instruments have revolutionized endodontic practice through continuous advancements in metallurgy and design. Despite these improvements, mechanical failure remains a clinical concern. This study aimed to evaluate and compare the design features, metallurgical properties, and buckling resistance of five widely used NiTi rotary endodontic systems.

Methods: A total of 250 new NiTi rotary instruments from five systems (ProTaper Next, Mtwo, ProFile, EndoSequence, and GT Series X) were analyzed. Design features were assessed using dental microscopy and scanning electron microscopy. Metallurgical properties were evaluated through energy-dispersive X-ray spectroscopy and differential scanning calorimetry. Buckling resistance was measured using a universal testing machine equipped with a 1 kN load cell, applying a compressive load at 1 mm/min until 1 mm of lateral displacement was achieved. Statistical analysis was performed using the Shapiro–Wilk test to assess normality, followed by the non-parametric Kruskal–Wallis test to compare groups. A significance level of $p < 0.05$ was adopted.

Results: ProFile instruments exhibited the highest number of spirals (19) and spiral density (1.19 spirals/mm), while GT Series X featured the shortest cutting blade length (≤ 12 mm). All systems demonstrated near-equiatomic nickel-titanium ratios. ProTaper Next and GT Series X showed higher R-phase and austenitic transformation temperatures. Buckling resistance was significantly greater in the ProFile (0.04 and 0.06 taper) and EndoSequence 35/.06 and 40/.06 instruments ($p < 0.05$). In contrast, EndoSequence 0.04 files, Mtwo, and ProTaper Next exhibited lower resistance.

Conclusion: Design features, taper, and metallurgical composition significantly influence the buckling resistance of NiTi rotary endodontic instruments.

Keywords: Buckling, differential scanning calorimetry, endodontics, energy-dispersive X-ray spectroscopy, scanning electron microscopy

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HIGHLIGHTS

- Advanced metallurgical treatments do not guarantee superior performance, ProTaper Next and GT Series X files with elevated R-phase and austenitic transformation did not show improved buckling resistance.
- The metallurgical treatments may influence the capabilities of an endodontic NiTi files, however the spiral density, cross sectional design and cutting blade length significantly affect the buckling strength.
- NiTi files with higher spiral density and greater taper showed superior buckling resistance but have reduced flexibility and potentially lower cutting efficiency.
- The study highlights the importance of selecting instruments to match specific clinical scenario, striking a balance between strength and flexibility.

INTRODUCTION

Mechanical instrumentation in endodontics has undergone significant advancements, particularly with the introduction and evolution of nickel-titanium (NiTi) files (1). In recent years, notable improvements in the quantity, quality, and design of these instruments have been achieved. Advances in metallurgy and design have led to the development of a wide variety of systems whose physical and metallurgical characteristics are fundamental to their clinical performance (2). These properties enable precise canal shaping, which is essential for effective irrigation and disinfection, particularly in anatomically complex root canals containing isthmuses, fins, and accessory canals (3, 4). The integration of mechanical instrumentation with appropriate disinfection protocols is critical for thorough microbial elimination, ultimately improving the success and quality of endodontic treatments (5, 6). Thus, the effectiveness of root canal therapy is closely tied to the physical and metallurgical attributes of the instruments employed (7).

Despite these advancements, all endodontic instruments remain prone to mechanical failure, particularly due to torsional stress and cyclic fatigue, which presents a significant challenge for clinicians (8, 9). Prior to the introduction of NiTi alloys, such failures were more frequently associated with stainless steel instruments, whose limited flexibility and fatigue resistance restricted their performance. The development of NiTi metallurgy has enabled the production of instruments with diverse designs, tapers, and heat treatments, which have significantly improved clinical outcomes by reducing the risk of iatrogenic complications such as canal deviation and perforation, while simplifying the shaping process (10). Nevertheless, NiTi instruments are not immune to deformation and fracture, necessitating ongoing innovation in their design and manufacturing to enhance both mechanical resilience and clinical reliability (11). To achieve these goals, manufacturers have employed techniques such as heat treatment, surface modification, and adjustments in instrument geometry and kinematics (12).

Among the many available systems, five widely used rotary NiTi instruments - ProTaper Next, Mtwo, ProFile, EndoSequence, and GT Series X - demonstrate notable differences in their metallurgical properties, cross-sectional design, and clinical performance. According to manufacturers and existing literature, ProTaper Next (Dentsply Maillefer, Ballaigues, Switzerland) incorporates proprietary M-Wire technology and an off-centered rectangular cross-section that facilitates debris removal while enhancing flexibility and cutting efficiency (13, 14). Mtwo (VDW, Munich, Germany) features an S-shaped cross-section with two active cutting edges and a small pitch, promoting preparation efficiency, stability, and debris elimination (15, 16). ProFile (Dentsply Maillefer, Ballaigues, Switzerland), the oldest system included in this study, is known for its excellent centering ability, particularly in canals with sharp curvatures. EndoSequence (Brasseler, Savannah, GA, USA) possesses a triangular cross-section with alternating contact points, electropolished surfaces for durability, variable pitch and helical angles, and a non-cutting tip to minimize canal aberrations (17). Finally, the GT Series X system (Dentsply

Maillefer, Ballaigues, Switzerland) features variable radial lands and an open-blade design that reduces threading and enhances cutting precision.

Despite these technological advancements, variability in instrument design, alloy treatment, and manufacturing processes can adversely affect mechanical properties such as flexibility, cyclic fatigue resistance, and cutting efficiency, ultimately impacting clinical outcomes (11). These inconsistencies may arise from pre-existing manufacturing defects or inappropriate clinical use. While most manufacturers adhere to rigorous quality control standards and perform *in vitro* testing before product release, batch-to-batch variability during mass production may still result in instruments with significant performance discrepancies.

One critical, yet often, overlooked mechanical property of endodontic instruments is buckling strength, which refers to the instrument's ability to withstand axial compressive forces without lateral deformation. During initial canal negotiation, glide path preparation, or retreatment procedures, particularly in constricted or calcified canals, files are frequently subjected to compressive stresses that may lead to buckling. An instrument with low buckling resistance may deflect prematurely, compromising directional control, reducing cutting efficiency, and increasing the risk of canal transportation or instrument fracture. Therefore, evaluating buckling resistance is essential to better understand the mechanical behavior of rotary NiTi files under clinically relevant loading conditions and to guide appropriate instrument selection based on procedural demands.

The NiTi systems examined in this study are considered "classic" instruments in contemporary endodontic practice, maintaining widespread clinical use years after their initial release. They have become reference standards against which newer systems are developed. Therefore, this study aims to evaluate and compare these five rotary NiTi systems in terms of design characteristics, metallurgical properties, and buckling strength, providing valuable insights for clinicians and researchers in selecting appropriate instruments for clinical applications.

MATERIALS AND METHODS

This study was conducted following the PRILE laboratory study guidelines (Fig. 1), a total of 250 brand-new 25-mm NiTi rotary endodontic instruments, differing in size, taper, and alloy heat treatment, were collected from five distinct multifile systems (ProTaper Next, Mtwo, ProFile, EndoSequence, GT Series X) for buckling testing, the inclusion of varying sizes and tapers was aimed to reflect the design differences among the brands included in the study as most endodontic files systems do not offer a directly comparable file with identical dimensions, and clinicians often choose instruments based on system-recommended protocols rather than uniform size specifications. Each endodontic file was inspected under a dental operating microscope (Opmi Pico, Carl Zeiss Surgical, Jena, Germany) at 13.6× magnification for any major defects that would necessitate exclusion from the

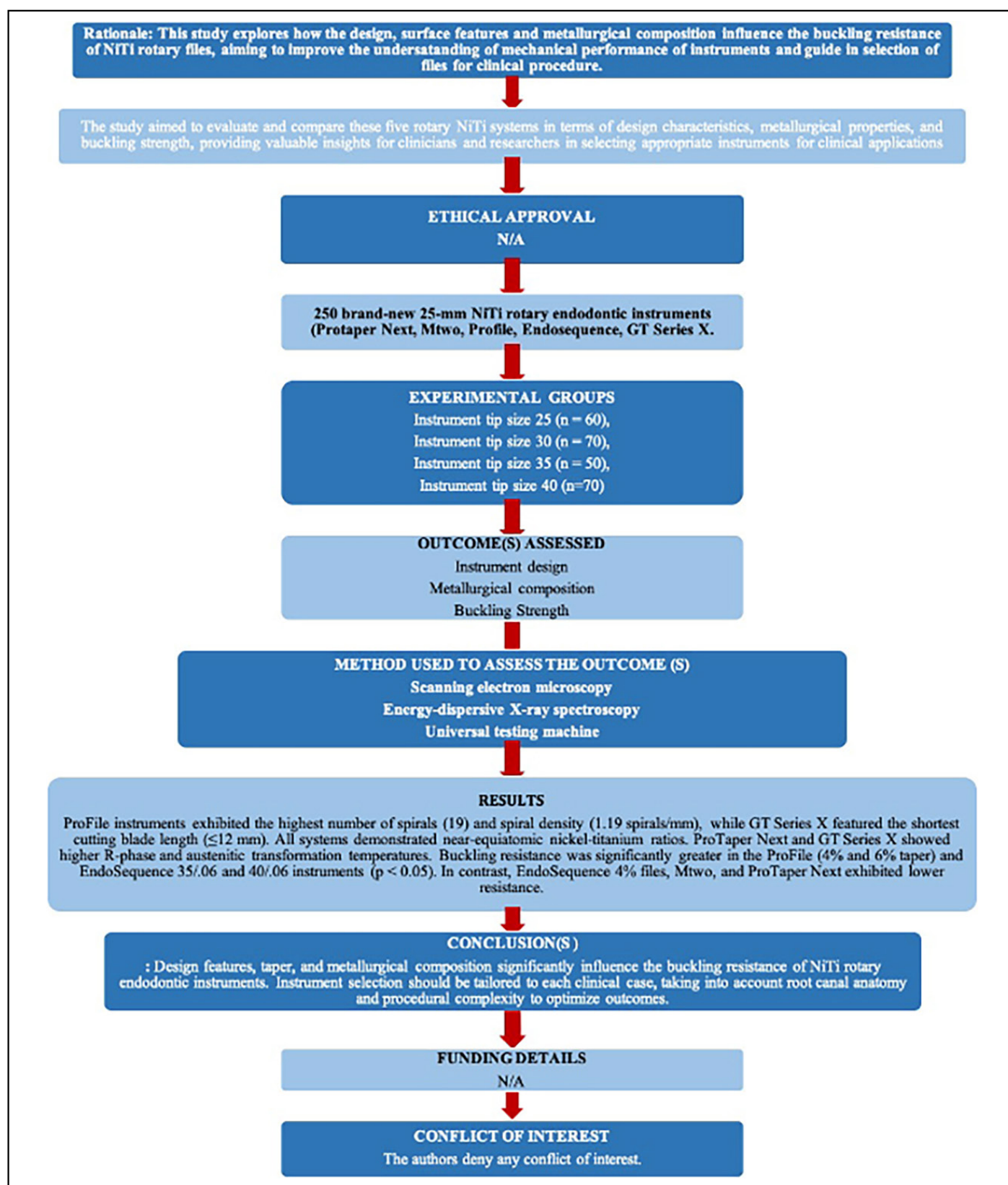


Figure 1. PRILE flow chart.

study; however, all instruments met the inclusion criteria.

Instrument's Design Assessment

Four files of each size were randomly chosen and inspected under a dental operating microscope (13.6× magnification) (Opmi

Pico, Carl Zeiss Surgical, Jena, Germany), with images recorded using a digital camera (Canon EOS 500D; Canon, Tokyo, Japan) to assess the cutting blade length, the total number of spirals, spirals per millimeter, and cutting spiral orientation. Next, the files were secured in a file holder and examined with a scanning elec-

tron microscope (150× magnification) (SEM) (S-2400, Hitachi, Tokyo, Japan) to evaluate surface finish and machining marks.

Metallurgical Assessment

The metallurgical features assessment was conducted on five reference endodontic files from each system (ProTaper Next X3 30/.07v, MTwo 30/.06, ProFile 30/.06, EndoSequence 30/.06 and GT Series X 30/.06). Only one reference file was selected per system, as each within a specific system undergoes identical metallurgical treatment.

A semi-quantitative elemental analysis was performed on three instruments from each system, utilizing energy-dispersive X-ray spectroscopy (EDS) with a standard scan electron microscope unit (DSM-962, Carl Zeiss Microscopy GmbH, Jena, Germany) equipped with an Inca X-act EDS detector (Oxford Instruments NanoAnalysis, Abingdon, United Kingdom). The device was operated at 20 kV and 3.1 amperes after a 10-minute vacuum preparation. Data collection took place over a 500 µm × 500 µm area for one minute, with a working distance set at 25 mm. Using the ZAF correction, the relative proportions of metallic elements were determined with specialized software (Microanalysis Suite v.4.14; Oxford Instruments NanoAnalysis, Abingdon, United Kingdom).

Differential scanning calorimetry (DSC) testing (DSC 204 F1 Phoenix; Netzsch-Gerätebau GmbH, Selb, Germany) was conducted to assess phase transformation temperatures, in accordance with ASTM F2004-17 (18) standards. A fragment of each instrument, 4 to 5 mm long and weighing 5 to 10 mg, was taken from the active blade and immersed in an etching solution (composed of 45% nitric acid, 25% hydrofluoric acid, and 30% distilled water) for 2 minutes. After neutralization in distilled water, each sample was placed in an aluminum pan within the DSC device, with an empty pan used as the control. The thermal cycle, spanning 1 hour and 40 minutes, was conducted under a nitrogen gas atmosphere. The temperature range for the cycle was set from -150°C to 150°C, increasing/decreasing at a rate of 10°C per minute. Netzsch Proteus Thermal Analysis software (Netzsch-Gerätebau GmbH) was used to process and generate DSC data and phase transformation temperatures graphs.

Buckling Assessment

The sample size was calculated based on the largest difference observed between two instruments in the initial five buckling tests. This calculation included the seven endodontic files with a tip size of 30 (ProTaper Next X3 30/.07v, MTwo 30/.06, ProFile 30/.04, ProFile 30/.06, EndoSequence 30/.04, EndoSequence 30/.06, and GT Series X 30/.06). With an alpha level of 0.05, a power of 80%, an effect size of 4.56, and a standard deviation of 2.63 (EndoSequence 30/.04 vs. ProFile 30/.06), a sample size of 7 instruments was calculated. As a result, 10 instruments per group were included in the final sample.

The buckling tests were conducted using a universal testing machine with a 1 kN load cell (Instron Corporation 4502; serial no. H3307, Bucks, England). Each instrument was positioned vertically, secured by the handle to the machine head, with the tip pointing downward into a small slot on a stainless-steel test base for stabilization (19). During testing, a compressive

load was applied at a rate of 1 mm per minute along the instrument's axis, from the handle toward the tip, until it achieved a lateral displacement of 1 mm. The peak buckling load was recorded in Newtons (N).

Statistical Analysis

The outcomes of the buckling test indicated a non-Gaussian distribution, as determined by the Shapiro-Wilk test. Results were presented as medians and interquartile ranges, and comparisons between groups, with the same apical size, were made using the nonparametric Kruskal-Wallis test. The significance level was set at 0.05 (SPSS v.22 for Windows; IBM SPSS Statistics, Chicago, IL, USA).

RESULTS

Instrument's Design Assessment

Analysis of the instrument designs showed that, with the exception of the GT Series X instruments, which had a cutting blade length of 12 mm or less, all other files had blades of 16 mm or more. The ProFile instruments had the highest number of spirals (19) and spirals per millimeter (1.19), while MTwo and EndoSequence files had the fewest (Table 1). All instruments had cutting blades oriented in a clockwise direction. In terms of microscopic surface finish and machining marks, the ProFile files displayed the most irregular surface, while the EndoSequence instruments had the smoothest surface (Fig. 2).

Metallurgical Assessment

EDS analysis indicated that all tested instruments were composed of a NiTi alloy, with near to equiatomic nickel and titanium ratios (ProTaper Next: 1.014; MTwo: 1.032; ProFile: 1.026; EndoSequence: 1.022; and GT Series X: 1.017), with no traces of other metallic elements (Fig. 3).

In the DSC tests, ProTaper Next and GT Series X instruments had the highest R-phase start (45.3°C and 50.2°C, respectively) and R-phase finish temperatures (16.3°C and 11.8°C, respectively), while the other instruments displayed R-phase starts at 27.9°C (EndoSequence) or lower. For the heating curves, ProTaper Next and GT Series X files also exhibited the highest austenitic start and finish temperatures (Fig. 3).

Buckling Assessment

The buckling test showed that ProFile 0.04 and 0.06 constant taper instruments, as well as the EndoSequence 35/.06 and 40/.06 files, had significantly higher results ($p < 0.05$) (Figs. 4, 5). The lowest results were observed in the EndoSequence 0.04 files, as well as in the MTwo and ProTaper Next instruments ($p < 0.05$) (Figs. 4, 5).

DISCUSSION

This study provides valuable insights into the relationship between design features, metallurgical properties, and buckling strength in five widely used NiTi rotary endodontic systems. The results revealed significant differences in mechanical performance, which appear to be closely related to variations in instrument design, surface characteristics, and metallurgical behavior.

The mechanical properties of endodontic instruments are known to be influenced by several key physical characteris-

TABLE 1. Instrument geometric features and buckling results (presented as median and interquartile range) of the assessed instruments

Endodontic instruments	Apical taper/variation*	Lot reference*	Cutting blade length (mm)	Number of spirals	Spirals per millimetre	Cutting blades direction	Buckling strength (Newton)
Instrument tip size 25 group							
ProFile	0.04	6519600	16	19	1.19	Clockwise	4.00 (3.87–4.03)
EndoSequence	0.04	0198	16	8	0.50	Clockwise	1.85 (1.43–2.03)
ProFile	0.06	1720487	16	19	1.19	Clockwise	3.80 (2.90–6.63)
EndoSequence	0.06	9376	16	7	0.44	Clockwise	2.80 (2.63–2.90)
ProTaper Next X2	0.06v	1515010	17	8	0.47	Clockwise	2.35 (2.10–2.40)
MTwo	0.07	363436	17	6	0.35	Clockwise	2.40 (2.08–2.83)
Instrument tip size 30 group							
ProFile	0.04	2725220	16	19	1.19	Clockwise	5.50 (4.58–6.00)
EndoSequence	0.04	0198	16	8	0.50	Clockwise	2.65 (2.48–2.90)
ProFile	0.06	060308511	16	19	1.19	Clockwise	6.50 (4.98–7.68)
EndoSequence	0.06	9376	16	7	0.44	Clockwise	3.60 (3.30–3.95)
GT Series X	0.06	SXRA525	12	8	0.67	Clockwise	4.10 (3.55–4.75)
ProTaper Next	0.07v	1515010	17	7	0.41	Clockwise	3.75 (3.50–3.90)
MTwo	0.06	362601	17	7	0.41	Clockwise	3.70 (3.38–3.80)
Instrument tip size 35 group							
ProFile	0.04	7235110	16	19	1.19	Clockwise	7.05 (5.70–8.00)
EndoSequence	0.04	0198	16	7	0.44	Clockwise	3.80 (3.40–4.10)
ProFile	0.06	1712662	16	19	1.19	Clockwise	7.75 (6.70–8.45)
EndoSequence	0.06	9376	16	6	0.38	Clockwise	7.65 (6.95–8.00)
MTwo	0.06	0903310641	17	8	0.47	Clockwise	4.40 (4.05–4.90)
Instrument tip size 40 group							
ProFile	0.04	7051790	16	19	1.19	Clockwise	9.55 (8.27–10.08)
EndoSequence	0.04	0198	17	6	0.35	Clockwise	5.70 (5.38–6.03)
ProFile	0.06	1686802	16	19	1.19	Clockwise	9.35 (8.60–10.70)
EndoSequence	0.06	9376	17	5	0.29	Clockwise	8.80 (7.85–9.73)
GT Series X	0.06	SXRA525	10	7	0.70	Clockwise	6.45 (5.80–7.10)
ProTaper Next X4	0.06v	1529960	18	7	0.39	Clockwise	6.15 (5.00–6.43)
MTwo	0.06	0904310642	17	8	0.47	Clockwise	5.05 (4.78–5.68)

*: Information from the manufacturer

tics, including tip diameter, taper, and manufacturing methods (20–22). Additionally, the length, number, and depth of spirals, as well as the orientation of the cutting blades, have a substantial impact on clinical performance (23, 24). An inverse relationship is often observed between spiral density and flexibility: while a greater number of spirals can theoretically enhance instrument resistance to deformation, lower resistance typically promotes smoother and more efficient canal shaping (25). This pattern was reflected in our findings. The ProFile instruments (with both 0.04 and 0.06 taper), along with the EndoSequence 35/.06 and 40/.06 files, exhibited superior buckling resistance—likely due to their higher spiral density and design geometry. In particular, ProFile's greater number of spirals per millimeter and total spiral count seemed to confer increased structural rigidity. However, SEM analysis revealed a relatively irregular surface finish, which, under high stress, has been identified as a critical factor contributing to fatigue failure (11).

These findings support prior research suggesting that spiral configuration and density are key determinants of instrument stiffness and deformation resistance (23, 24). However, they also raise a critical consideration: while increased structural integrity may improve resistance to buckling, it may simulta-

neously reduce cutting efficiency and hinder debris removal. This underscores the need for balance between mechanical robustness and clinical functionality.

The metallurgical assessment revealed a possible link between phase transformation temperatures and mechanical behavior. ProTaper Next and GT Series X instruments exhibited higher R-phase and austenitic transformation temperatures compared to the other systems. Nevertheless, this did not correspond to higher buckling resistance, suggesting that metallurgical factors alone may not be the primary determinants of axial stability. Instead, features such as cross-sectional design and surface finish may play more significant roles. These findings challenge the assumption that advanced heat treatments automatically translate to superior mechanical performance. Moreover, the near-equiatomic nickel-titanium ratios observed across all systems indicate that compositional differences were minimal and unlikely to drive mechanical variability.

The lower buckling resistance observed in EndoSequence 0.04 files, Mtwo, and ProTaper Next instruments presents both clinical benefits and drawbacks. Despite EndoSequence's smooth surface finish, its 0.04 taper variants demonstrated lower resistance compared to their 0.06 counterparts, suggesting that

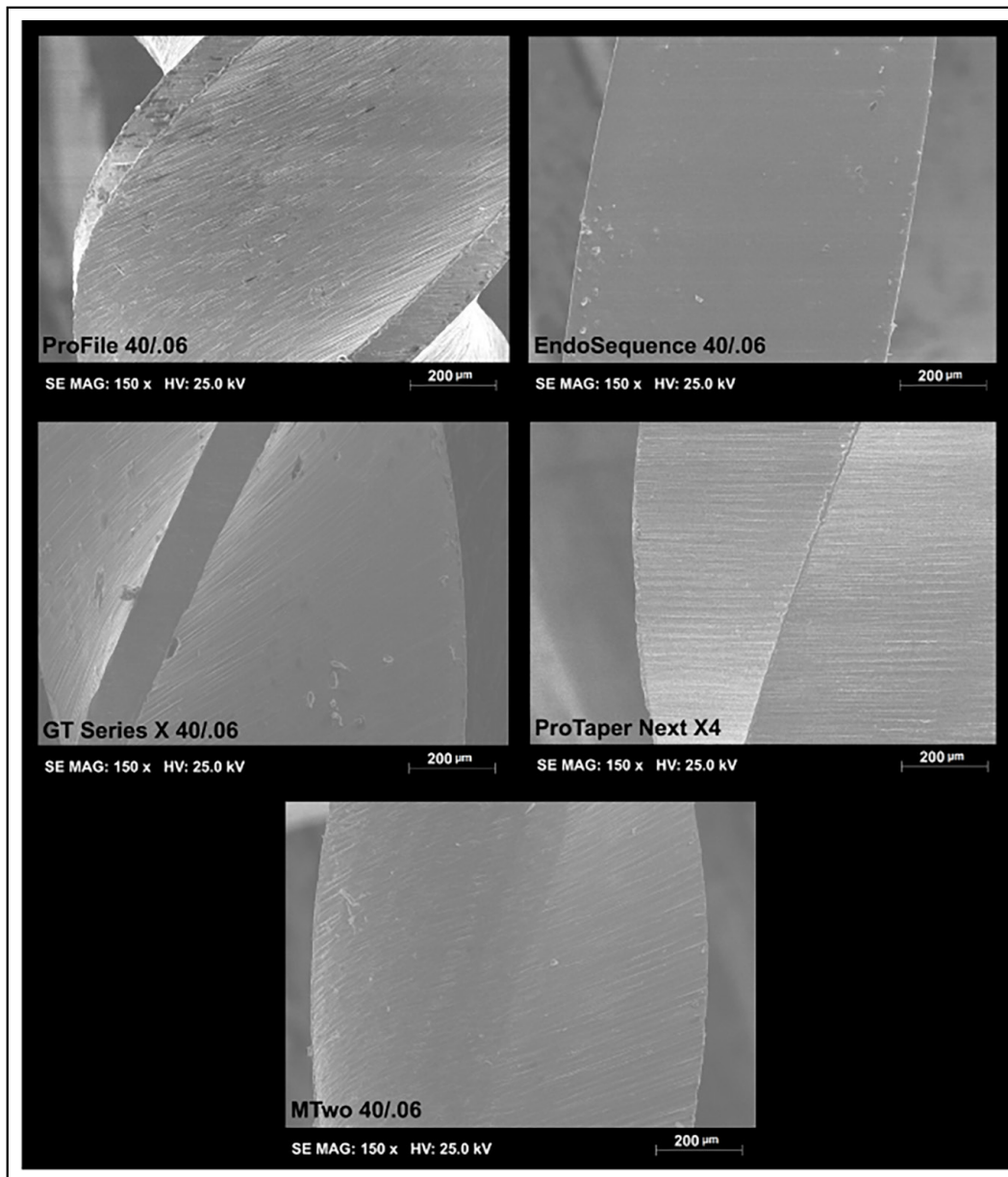


Figure 2. Representative images of the surface finish for instruments from each multifile system. ProFile instruments generally showed the most irregular surfaces, while EndoSequence instruments appeared to have the smoothest.

taper has a more substantial impact on mechanical behavior than surface treatment alone. Similarly, the reduced buckling resistance of ProTaper Next, despite its M-Wire technology, may be attributed to its off-centered rectangular cross-section. While this design enhances flexibility and debris removal, it appears to compromise axial stiffness. These observations raise further questions about the trade-offs inherent in instrument design. Some clinicians may favor increased flexibility in curved canals to avoid transportation or perforation, while others may prioritize structural stiffness to ensure control in calcified or straight canals (26, 27). This ongoing debate emphasizes the importance of selecting instruments based on case-specific anatomical and procedural demands.

An interesting observation arose from the analysis of cutting blade length. According to Euler's buckling theory, longer instruments are more susceptible to lateral deformation under

axial load (28). Based on this principle, GT Series X files, having the shortest cutting blade length (≤ 12 mm), might be expected to show greater resistance to buckling. However, our findings did not support this hypothesis. These instruments did not outperform those with longer blade lengths (≥ 16 mm), suggesting that the correlation between blade length and buckling resistance is more complex than previously thought. It may be that the formula applies more directly to the total instrument length rather than the active blade segment. Other design parameters, such as cross-sectional geometry and core diameter, likely also influence axial stability (26, 29, 30).

From a clinical standpoint, our findings have important implications for instrument selection and usage. Instruments like ProFile and EndoSequence with a 0.06 taper, which demonstrated superior buckling strength, may be more suitable in cases that require enhanced structural rigidity, such as retreat-

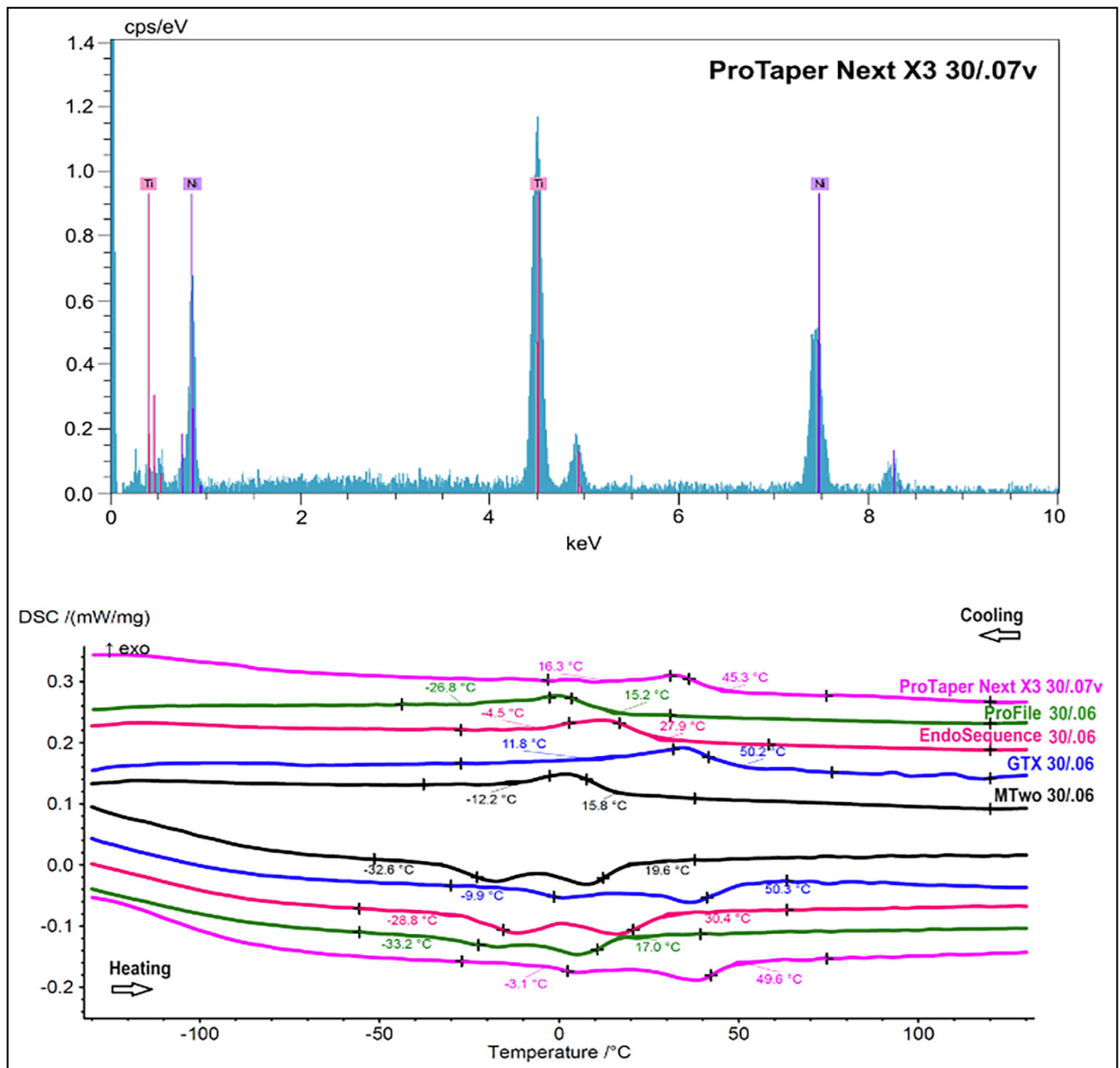


Figure 3. The metallurgical assessment confirmed the presence of NiTi alloys in all tested instruments, each with distinct phase transformation temperatures. At the top, a representative EDS spectrum highlights the nickel and titanium elements; spectra from all instruments were consistent with this example. Below, the DSC chart shows that GT Series X and ProTaper Next instruments had the highest phase transformation temperatures (the chart reads right to left on the cooling curve and left to right on the heating curve).

DCS: Differential scanning calorimetry, GTX: GT Series X, EDS: Energy-dispersive X-ray spectroscopy.

ment procedures or the removal of gutta-percha. However, it is important to recognize that greater buckling resistance may limit flexibility, which can be a disadvantage in curved or narrow canals. Therefore, maintaining a versatile set of instruments is crucial to accommodate a variety of anatomical and procedural scenarios.

Moreover, our results emphasize that when evaluating endodontic instruments, clinicians and researchers must consider multiple factors. While metallurgical treatments and

surface modifications certainly contribute to performance, basic design features such as taper, spiral configuration, and cross-sectional shape may exert more significant influence on buckling behavior.

A limitation of this study is its exclusive focus on buckling resistance as the primary mechanical parameter. While valuable, this single metric provides an incomplete view of an instrument's clinical performance. Other factors, including core diameter, cutting efficiency, torsional strength, and

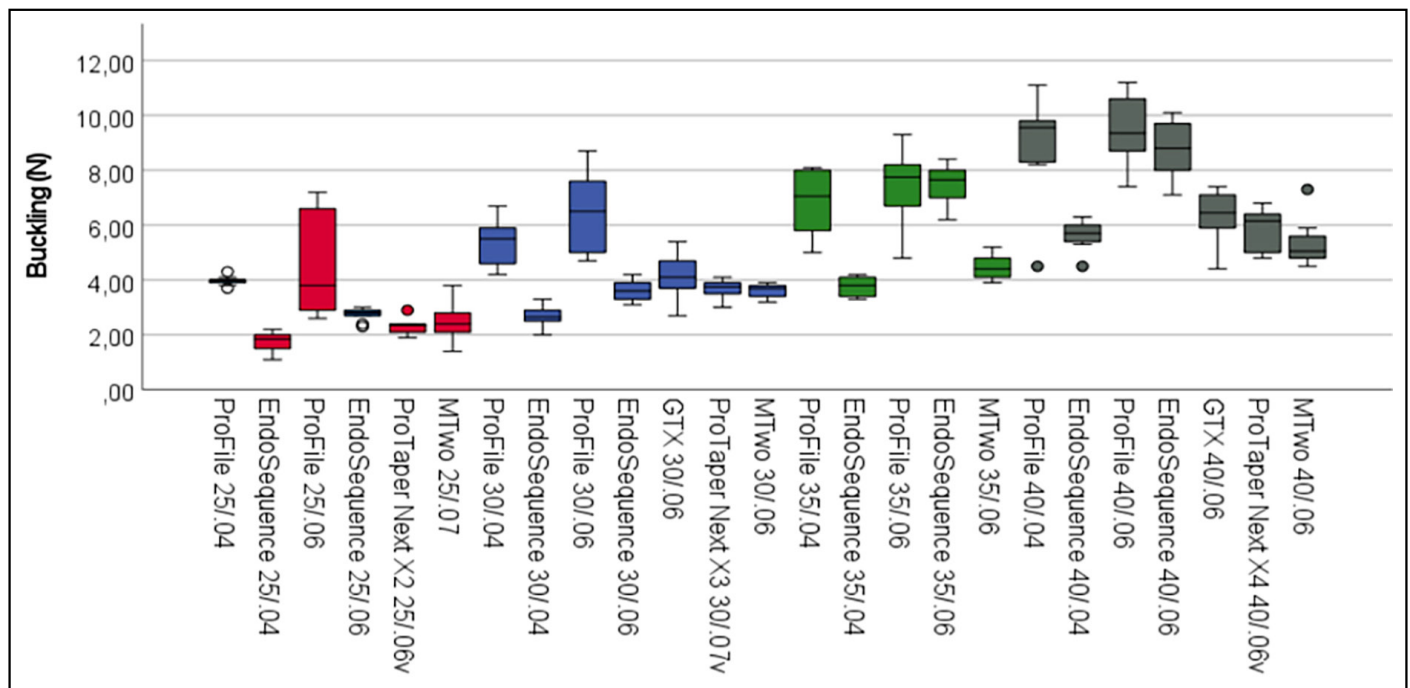


Figure 4. Box plot charts displaying the buckling test results reveal a trend of higher values for ProFile 0.04 and 0.06 instruments and lower values for EndoSequence 0.04 files.

GTX: GT Series X.

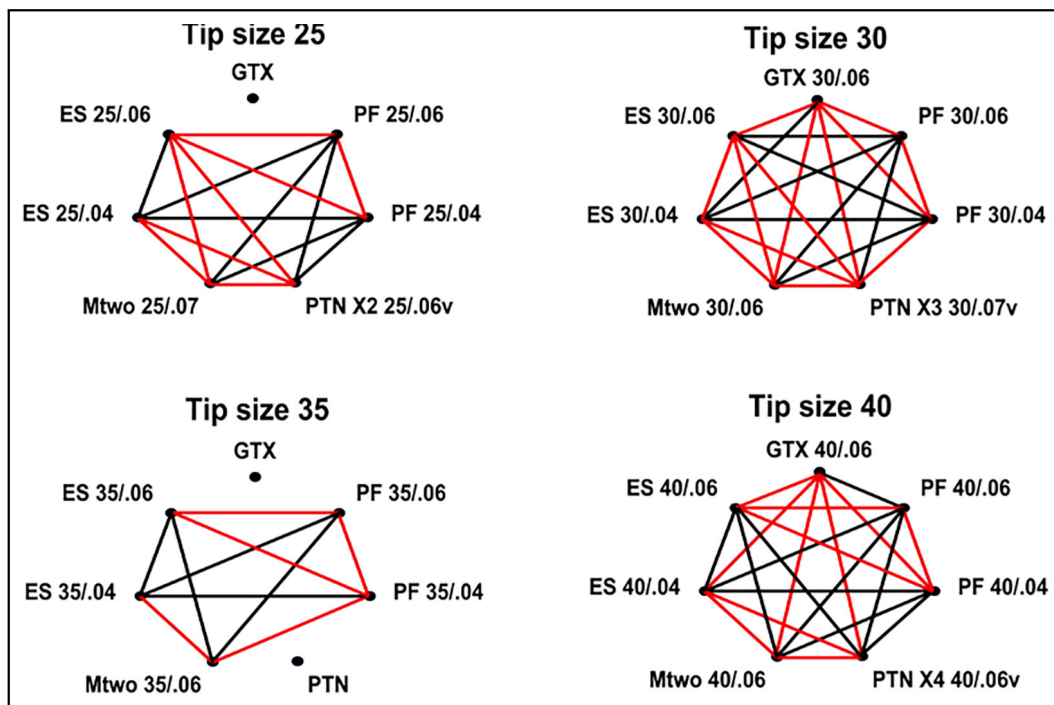


Figure 5. Pairwise comparisons between groups with the same apical size (GTX GT Series X, PF ProFile, PTN ProTaper Next, ES EndoSequence).

GTX: GT Series X, PF: ProFile, PTN: ProTaper next.

fatigue resistance, are also critical to endodontic success. Nonetheless, our findings offer useful data that may inform future instrument development and support improvements in design for enhanced clinical reliability. Additionally, as this investigation was conducted under controlled laboratory conditions, it may not fully replicate the challenges

presented in clinical environments. Future research should consider exploring the influence core diameter of these endodontic files and also incorporate studies in simulated or real canal anatomies to better validate these *in vitro* findings and expand our understanding of how these instruments perform under diverse clinical conditions.

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