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Fracture resistances of heat-treated nickel-titanium files used for minimally invasive instrumentation

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Abstract

Background This study compared the torsional resistance, bending stiffness, and cyclic fatigue resistances of different heat-treated NiTi files for minimally invasive instrumentation.

Methods TruNatomy (TN) and EndoRoad (ER) file systems were compared with ProTaper Gold (PG). Torsional load, distortion angle, and bending stiffness were assessed using a custom device AEndoS, and toughness was calculated using the torsional data. Cyclic fatigue resistance was evaluated using another custom device (EndoC) with 45-degree curved canal in which file was rotated until fracture using dynamic pecking motion at 37 °C. One-way analysis of variance and Duncan's post-hoc comparison were conducted at a significance level of 95%. Scanning electron microscopy (SEM) analyzed fracture features and differential scanning calorimetry (DSC) analyzed phase transformation temperatures.

Results ER and TN showed significantly lower torsional strength than PG ($p < 0.05$). However, ER showed a significantly greater distortion angle and the highest toughness, followed by PG and TN ($p < 0.05$). Both ER and TN showed similar bending stiffness, which was lower bending stiffness than PG ($p < 0.05$). ER showed the highest cyclic fatigue resistance ($p < 0.05$). SEM revealed typical fracture features across all groups, with distinct milling grooves in PG and TN, not in ER. DSC indicated that PG and ER showed a peak of austenite (A*p*) at temperatures higher than body temperature, 42 °C and 40 °C, respectively, while TN showed A *p* at 25 °C.

Conclusion Files for minimally invasive instrumentations typically exhibited high cyclic fatigue resistance but showed differences in the properties. The selection should depend on the root canal and tooth condition.

Keywords Bending stiffness, Heat treatment, Minimal invasive, Torsional resistance, Cyclic fatigue

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Background

Recently, the concept of minimal invasiveness has been introduced in dentistry and it has been applied in various practical dentistry, including restorative dentistry and implant surgery [1]. Minimally invasive endodontic treatment has been also introduced to clinical dentistry to increase the preservation of tooth material for better prognosis of endodontically treated teeth (ETT) [2, 3].

Various kinds of access cavity designs, such as conservative and truss access, have been proposed to preserve coronal tooth structure [3, 4]. The fracture resistance of an ETT was increased by preparing the conservative endodontic access cavity [3–5]. Minimally invasive access was reported to maintain coronal dentin and offer increased fracture resistance of ETT [4–6]. In these minimally invasive approaches to access cavity preparation, while the smaller size from the occlusal surface is the main approach, different access directions and locations were attempted depending on cases (mainly, caries location) in anterior teeth and premolar [5, 7–9].

During the root canal preparation procedure after access cavity preparation, instrumentation methods and/or instruments themselves have been reported as to be related to the reduced resistance to mechanical failure of the ETT [10, 11]. The potential risk of root dentin crack or vertical root fracture (VRF) from endodontic treatment due to excessive canal preparation has been reported [10, 12]. A certain size of an instrument under certain canal conditions may have a higher potential risk of root dentin damages [10, 11]. To reduce this kind of unfavorable situation, martensite dominant nickel-titanium (NiTi) files were developed through various heat treatments and geometric alterations [13, 14]. These heat-treated files have been reported to have several advantages, such as maintaining the center of the canal well to prevent it and causing less transportation or development due to their lower stiffness and higher ductility than the files made of conventional NiTi alloy [11, 13–15].

Meanwhile, the preservation of peri-cervical dentin (PCD) has been suggested as an important anatomical structure for the long-term prognosis of the ETT [6, 9]. Preservation of PCD has been reported to reduce VRF in the tooth and prolong the prognosis after root canal treatment [16, 17]. According to the minimal invasiveness concept, the usage of reduced-tapered NiTi files and conservative endodontic access cavity preparation has gained popularity.

Recently, some NiTi file systems in the form of smaller tapers and thinner shafts were introduced to preserve PCDs and consequently have a better prognosis for the ETT. It was suggested that minimally invasive root canal preparation performed using NiTi files with a smaller taper may preserve the root dentin tissue compared to that of larger tapered NiTi files and increase the fracture resistance of the ETT [18–20].

TruNatomy system (Dentsply Sirona, Ballaigues, Switzerland) is designed to preserve PCDs and increase file flexibility by reducing the diameter of file shaft from approximately 1.2 mm to 0.8 mm, followed by a post-manufacturing heat treatment. TruNatomy file has a square cross-section with an off-center design, a variable taper and 4% taper at apical few millimeters [21, 22]. Another instrument system aimed at minimal invasive root canal shaping, EndoRoad (Maruchi, Wonju, Korea) made of MT-wire (by memory-triple heat treatment technology as named by the manufacturer) with surface treatment was recently introduced [23]. EndoRoad file system has a triangular cross-sectional shape with increased ductility achieved by using the heat-treated alloy (MT-wire) at body temperature [23, 24].

Typically, files with thinner shafts and/or smaller cross-sectional areas have lower torsional strength and higher fatigue resistances, as reported by geometric optimization studies [25–27]. This relationship is primarily attributed to the reduction in metal mass, which decreases rigidity and enhances flexibility. However, these studies have predominantly focused on general file designs, and there is a notable lack of research specifically addressing files designed for minimally invasive root canal procedures. Files that underwent specialized heat treatments and surface modifications are especially noteworthy, as these processes have the potential to significantly modify their mechanical properties, such as torsional strength and cyclic fatigue resistance.

The purpose of this study was to compare the torsional fracture resistance, bending stiffness, and cyclic fatigue resistance of heat-treated NiTi files for minimally invasive instrumentation with a common heat-treated NiTi instrument system (ProTaper Gold; Dentsply Sirona). The null hypothesis was that all of these heat-treated NiTi files have the same mechanical properties.

Materials and methods

Two file systems with a minimally invasive concept were used in this study: TruNatomy (TN; Prime, #26/.04v) and EndoRoad (ER; #25/.06v). They were compared with ProTaper Gold (PG; F2, #25/.08v; Dentsply Sirona), which is one of the popular systems as contemporary heat-treated file systems [12]. All three file systems have a shaft length of 25 mm and a similar tip size of the International Organization for Standardization (ISO) #25.

Before the test, all instruments were inspected under a dental operating microscope (M320; Leica Microsystems, Wetzlar, Germany) at ×10 magnification to confirm that there was no deformation of the files.

Table 1 provides the manufacturers' descriptions for each of these files. Sample size calculations were

Table 1 The characteristics of each file used in this experiment

File	Tip size (ISO)	Apical taper	Shaft diameter	Cross-section
EndoRoad	25	6% and variable	0.8 mm	Triangle
TruNatomy	26	4% and variable	0.8 mm	Square and off-centered
ProTaper Gold	25	8% and variable	1.2 mm	Convex triangle

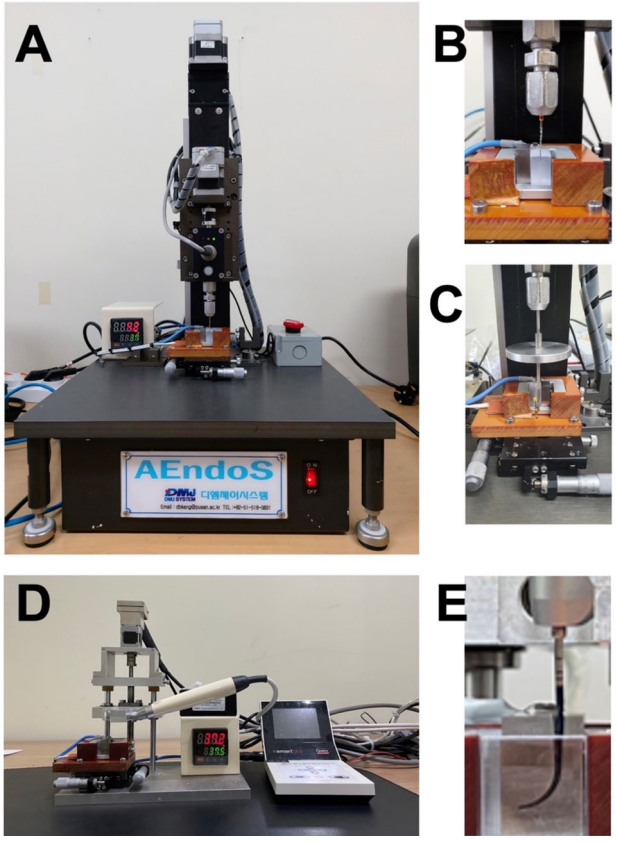

Fig. 1 Experimental setup for this study. (**A**) AEndoS was used with the jigs for testing (**B**) torsional resistance and (**C**) bending stiffness. (**D**) EndoC was used for the cyclic fatigue tests, along with an (**E**) artificial canal featuring a 45° angle of curvature. Temperature controlling sensor and heat generator were attached to both of the test devices

conducted using G*Power 3.1 software (Heinrich-Heine-Universität, Düsseldorf, Germany). With an α level of 5%, a β level of 20%, and the chosen effect size, the required total sample size was determined to be 12. Therefore, each group in this study consisted of 15 files.

In this study, torsional resistances, bending stiffness, and cyclic fatigue resistance were compared using customized devices (AEndoS and EndoC; DMJ System, Busan, Korea) (Fig. 1). AEndoS was used for the torsional test and bending stiffness measurement test with dedicated jigs. EndoC was used for cyclic fatigue resistance with a simulated canal. All the experiments were carried out in a heat-controlled environment similar to the intraoral temperature (37℃). The temperature was controlled using a thermal sensor and heat generator attached to the test devices.

Torsional resistance test

For the torsional resistance test, the torsional strength and distortion angle were measured using the AEndoS (Fig. 1A and B) ($n = 15$). The file tip of 3 mm was fixed between copper plates and driven clockwise at 60 rpm until fracture occurred [28]. While the files rotated, the torsional load (Ncm) and distortion angle (°) were recorded at a speed of 50 Hz. The toughness until fracture was numerically calculated from the area under the plot presenting distortion angle (X axis) and torsional load (Y axis) using Origin v6.0 Professional (Microcal Software Inc, Northampton, USA) [17].

Bending stiffness test

The bending stiffness was measured also with the AEndoS (Fig. 1A and C) following the American National Standard/American Dental Association specification no. 28 and ISO specification 3630-1:2008 [28, 29]. The file tip of 3 mm files was fixed between two resin blocks and bent at 45° to their long axis. After bending the file 45°, the angle between the location of the bent file and the initial location was defined as the residual angle ($n = 15$). To measure the residual angle, the distance between the initial location of the file and the location after bending was measured using a micro-caliper. The residual angle was calculated using the Pythagorean method.

Cyclic fatigue resistance test

Cyclic fatigue resistance was evaluated in another custom-made device, EndoC (Fig. 1D). Cyclic fatigue resistance was tested by pecking and rotating instruments in an artificial canal with a 7.8 mm radius and a 45° angle of curvature until fracture (Fig. 1E). The instruments from each group ($n = 15$) were rotated in a pecking motion using an endodontic motor and handpiece (X-smart Plus; Dentsply Sirona) at speeds of 600 revolutions per minute (rpm), 500 rpm, and 300 rpm for ER, TN, and PG, respectively. The pecking distance comprised a 4 mm increment in each direction every 0.5 s, with a 50 ms dwell time. The moment the instrument was broken was recorded using a chronometer. The number of cycles to failure (NCF) was calculated by applying the rotation speed and time (seconds) to fracture.

Scanning electron microscope (SEM) observation

After the torsional and cyclic fatigue tests, the fractured files underwent examination via scanning electron microscopy (SEM). Before microscopic observation, all the files were subjected to a cleaning process with absolute alcohol and immersion in an ultrasonic bath

to eliminate any debris. Subsequently, the files were left to air dry at room temperature and attached onto metal plates using double-sided adhesive carbon tape. The mounted samples were then placed inside the SEM (JSM-7200 F: JEOL, Tokyo, Japan). Finally, four fractured fragments from each group were observed under the SEM in various magnification ranges to assess the topographic features of the surface.

Differential scanning calorimetry

Differential scanning calorimetry (DSC) analysis was performed to determine phase transformation temperatures. Specimens from three groups were analyzed (DSC Q2000 V24.4 Build 116; TA Instruments, New Castle, USA) to obtain the features of austenite peak (A*p*) temperature during heating and cooling curves.

To determine various temperature points, including the austenite starting temperature (A*s*), austenite finishing temperature (A*f*), R-phase starting temperature (R*s*), R-phase finishing temperature (R*f*), martensite starting temperature (M*s*), and martensite finishing temperature (M*f*), a specific method was employed. Referring to earlier our laboratory tests, the maximum temperature during calorimetric heating was determined to be 80 °C, which was higher than the temperature required to achieve a fully austenite state for each of the studied specimens [30, 31].

Statistics analysis

The normality of the data was assessed using Levene test. In cases of normal distribution, for data evaluation and comparison among the file groups, one-way analysis of variance and Duncan's post-hoc comparison were conducted using statistic program SPSS (version 25.0; SPSS Inc., Chicago, IL). Statistical significance was set at 95%.

Results

Using descriptive statistics, the average and standard deviation results from the three tests are shown in Table 2.

PG showed the highest ultimate torsional strength, followed by the ER and TN ($p < 0.05$). ER showed a significantly greater distortion angle than TN and PG. ER showed the highest toughness, followed by PG and TN, in the order ($p < 0.05$).

ER and TN showed significantly lower bending stiffness than PG ($p < 0.05$). ER and TN had similar bending stiffness. ER showed higher residual angles than PG and TN ($p < 0.05$). ER showed the highest cyclic fatigue resistance, followed by PG and TN ($p < 0.05$).

SEM examination of the fractured fragments after the torsional resistance tests showed typical features of torsional fractures, such as concentric abrasion marks and fibrous dimples from the torsional center (Fig. 2). In the lateral aspects, while the PG and TN showed distinct milling grooves and curved and slippery was observed. However, ER group did not present the milling groove and slippery. SEM examination of the cyclic fatigue fracture fragments showed typical features of fatigue fractures, such as crack initiation area(s), fatigue zone, and rolled over fast fracture area (Fig. 3).

The results of the DSC analysis exhibited a distinct difference in phase transformation temperatures for all groups (Fig. 4). DSC analysis showed that PG and ER showed a peak of austenite (A*p*) at temperatures higher than body temperature, 42 °C and 40 °C respectively. TN showed A*p* at 25 °C, in a relatively low temperature.

Discussion

The primary goal of endodontic treatment to save a natural tooth is the removal of bacterial infection from the root canal system. After root canal treatment, the restoration of the tooth function and prevention of reinfection are essential. ETT should be reinforced by restorative treatments such as intra-coronal or full veneer restorations, to ensure proper coronal sealing [30]. The durability and prognosis of the ETT should be considered when selecting materials and methods for these post-endodontic restoration procedures [9, 16, 17, 19, 30].

Minimally invasive endodontic procedures primarily consist of access cavity preparation and root canal instrumentation [6, 8, 9, 16]. Many studies have investigated access cavity designs to increase mechanical resistance under occlusal loading using in-vitro tests and finite element analysis [8, 17, 19]. However, there is a lack of sufficient studies examining the effects of different file

Table 2 Torsional resistances, bending stiffness, and cyclic fatigue resistance of the tested files (mean ± standard deviation)

System	Torsional resistance			Bending stiffness		Cyclic fatigue resistance
	Ultimate strength (*N*·cm)	Distortion angle (°)	Toughness (°*N*·cm)	Residual angle (°)	Bending stiffness (*N*·cm)	Number of cycles to fracture (NCF)
EndoRoad	1.24 ± 0.16^{b}	1210 ± 180^{a}	967 ± 233^{a}	28.42 ± 1.69^{a}	0.50 ± 0.07^{a}	2548 ± 292^{a}
TruNatomy	0.56 ± 0.03^{c}	495 ± 43^{b}	186 ± 22^{c}	1.44 ± 0.69^{c}	0.48 ± 0.17^{a}	519 ± 54^{c}
ProTaper Gold	1.63 ± 0.11^{a}	351 ± 25^{c}	356 ± 38^{b}	4.67 ± 0.94^{b}	1.32 ± 0.24^{b}	982 ± 53^{b}

[abc]: different superscript letters indicate statistical differences between groups ($p < 0.05$)

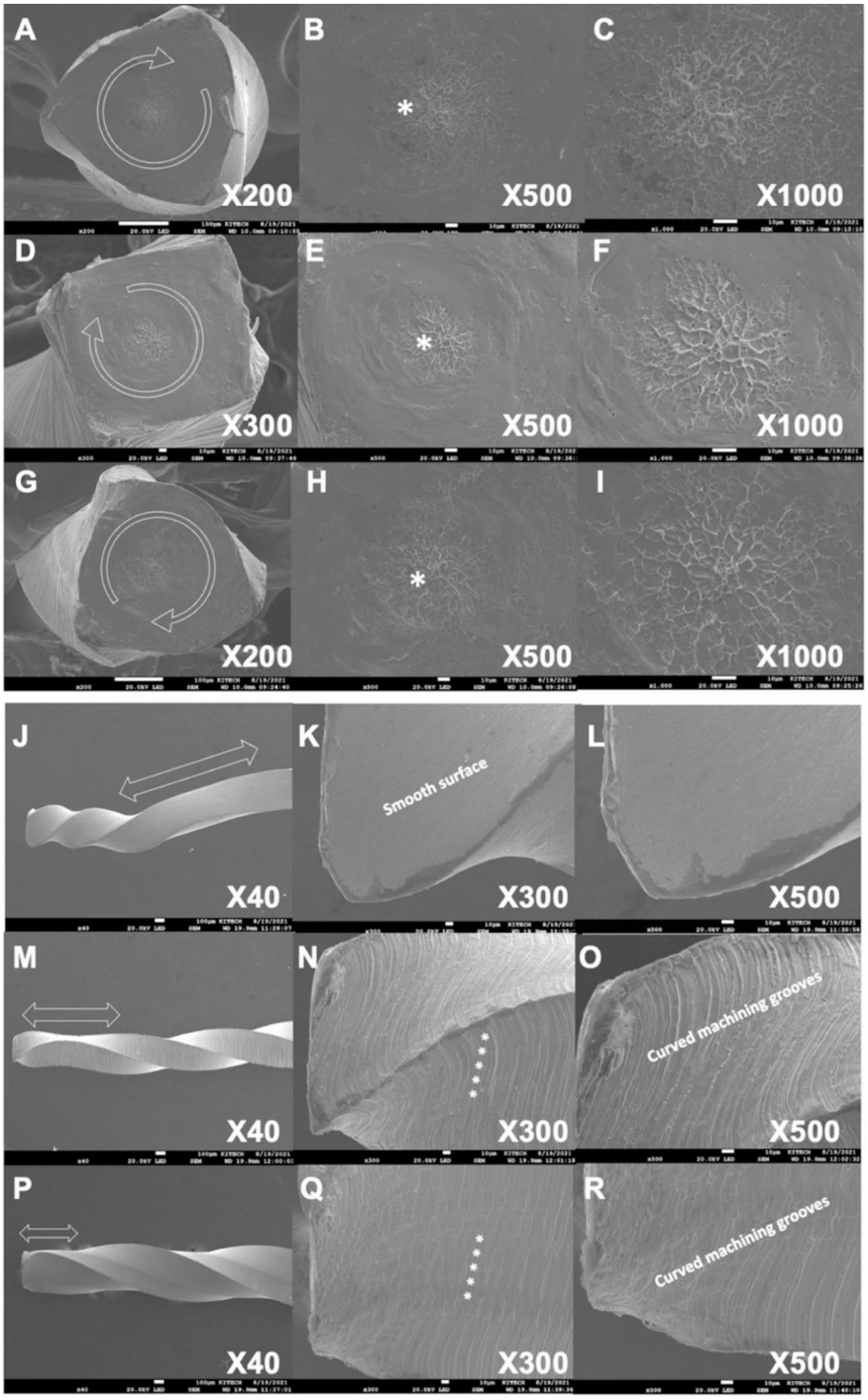

Fig. 2 Cross-sectional aspects (EndoRoad: **A**, **B**, **C**; TruNatomy: **D**, **E**, **F**; ProTaper Gold: **G**, **H**, **I**) and longitudinal aspects (EndoRoad: **J**, **K**, **L**; TruNatomy: **M**, **N**, **O**; ProTaper Gold: **P**, **Q**, **R**) of scanning electron microscope (SEM) images of separated fragments after torsional resistance test. (**A**, **D**, **G**) The circular arrow indicates the concentric abrasion mark. (**B**, **E**, **H**) Numerous fibrous dimples (*) were found at the center of rotation and (**C**, **F**, **I**) in the magnified views. (**J**, **M**, **P**) Double sided arrow indicates the unwound helix. EndoRoad shows a much longer unwound helix than the others. (**K**) EndoRoad shows a smooth surface, while others show machining grooves. (**N** and **O**) TruNatomy and (**Q** and **R**) ProTaper Gold show machining grooves curved (*****) by the torsional loads

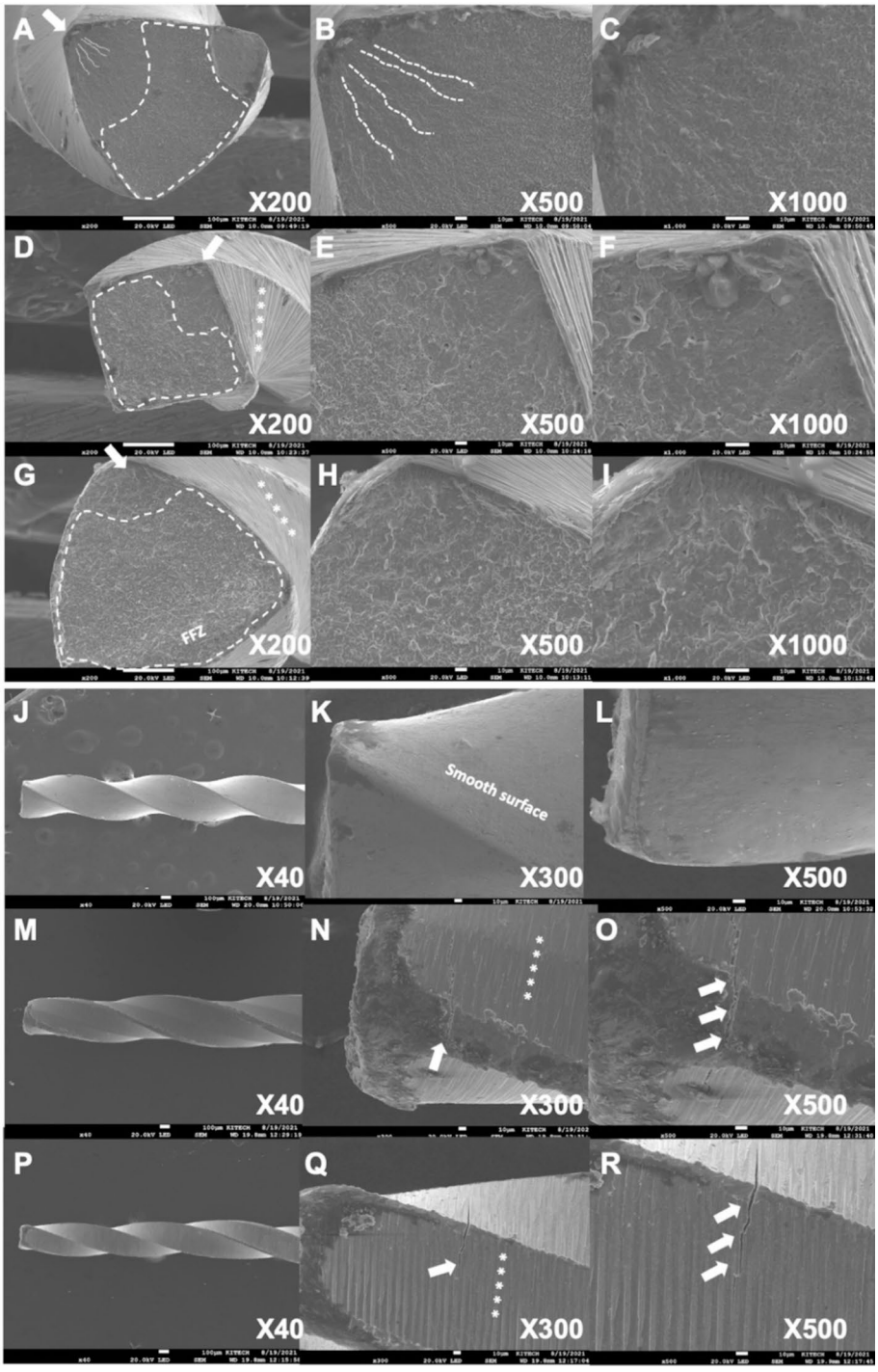

Fig. 3 Cross-sectional aspects (EndoRoad: **A**, **B**, **C**; TruNatomy: **D**, **E**, **F**; ProTaper Gold: **G**, **H**, **I**) and longitudinal aspects (EndoRoad: **J**, **K**, **L**; TruNatomy: **M**, **N**, **O**; ProTaper Gold: **P**, **Q**, **R**) of scanning electron microscope (SEM) images of separated fragments after cyclic fatigue resistance test. (**A**, **D**, **G**) Arrow indicates the crack initiation area and encircled area with dot-line indicates fatigue zone and (**G**) ProTaper Gold shows rolled-over fast fracture zone (FFZ). (**A**, **B**) EndoRoad shows crack propagation area with river-flow like striation marks. (**J**, **M**, **P**) Helix without unwound area near the fractured end. (**K**) EndoRoad shows smooth surface while others show numerous machining grooves (*****). (**N**, **O**, **Q**, **R**) Arrows indicate the microcracks running alongside the machining grooves

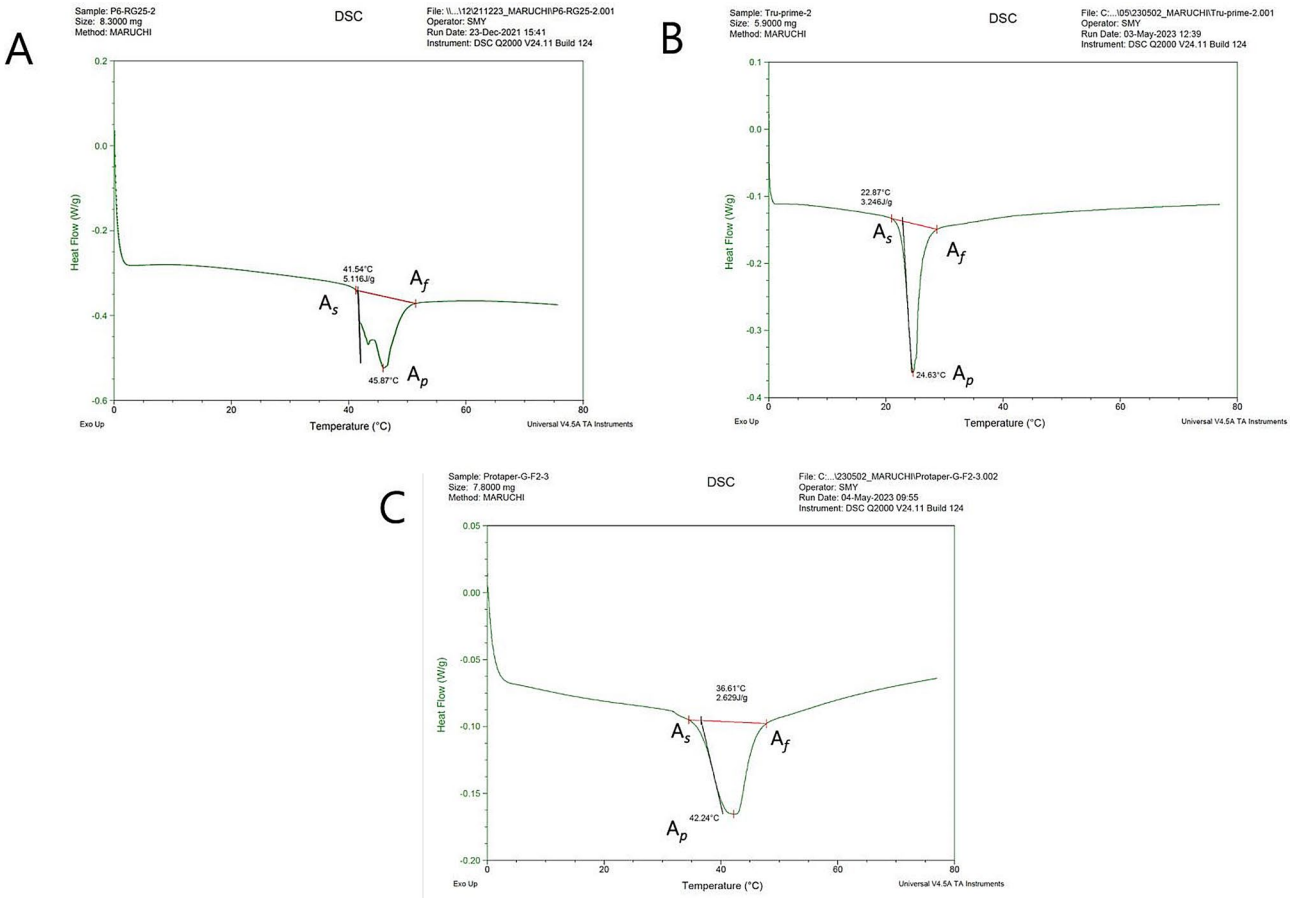

Fig. 4 Representative heating curves from differential scanning calorimetry of (**A**) EndoRoad, (**B**) TruNatomy Prime, and (**C**) ProTaper Gold before experiment (A*s*: austenite start temperature; A*p*: austenite peak temperature; A_f: austenite finish temperature)

systems and apical root canal preparation on extending the mechanical durability of ETT [16, 20].

This study compared the mechanical properties of NiTi files recently developed with the concept of minimal invasiveness. These files may have different mechanical properties due to their thinner and smaller size compared to conventional and traditional NiTi files, aimed at preserving the root dentin's PCD during instrumentation [5, 7, 16, 23, 24].

Silva et al. [32] reported that minimal endodontic access cavities may increase the remaining root dentin and, consequently, reduce the fracture of ETT. Thus, manufacturers have developed files with relatively thin shafts, with the maximum flute diameter (MFD) reduced to 0.8 mm instead of usual 1.2 mm for most generic variable tapered files [33]. While these small-sized instruments generally exhibit high fatigue resistance and flexibility, they may have lower torsional strength [10, 26, 27]. In conclusion, each file used in the experiment exhibited differences in physical properties based on heat treatment and cross-sectional area. Therefore, the null hypothesis was rejected.

In this study, PG was used for comparison, although it does not adhere to the minimally invasive concept, serving as a comparison/control group due to its common size and composition of heat-treated alloy (Gold wire). Including PG, TN and ER were evaluated for the mechanical properties of torsional resistance, bending stiffness, and flexural fatigue resistance.

Torsional resistance assesses the ability to withstand distortion or fracture when a file becomes stuck in the root canal, particularly focusing on ductility that can affected by heat treatment [21, 22]. This is an important aspect for the thin file systems because they usually have lower torsional strength and are at risk of unwinding or distortion in tight canal conditions [21, 26]. Bending stiffness measures flexibility, while cycle fatigue resistance evaluates the ability to resist fractures from repeated bends in curved root canals [27].

In this study, PG showed the higher ultimate torsional strength than ER and TN ($p < 0.05$). This difference can be attributed to the larger cross-section of PG, which usually has higher torsional resistance compared to files with smaller cross-Sects. [26, 34, 35]. Meanwhile, ER showed a significantly greater distortion angle than TN and PG,

leading to higher toughness, attributable to its heat treatment. From the perspective of toughness—a composite parameter of torsional resistance—this increase in flexibility through heat treatment is particularly significant, as it enables the file to better endure torsional stress [34]. Thus, clinicians using heat-treated files may have a better chance of identifying distorted file before fractures occur, thereby improving both safety and performance during clinical procedures.

As found in the bending stiffness test, ER has a lower bending stiffness and larger residual angles compared to PG and TN. These characteristics contributed to ER showing the highest cyclic fatigue resistance than others. This outcome could be attributed to ER's thin geometry and the properties of heat-treated NiTi alloy. However, TN showed lower fatigue resistance than ER and similar resistance to PG, contrary to expectations based on their geometries and alloy characteristics. The lower fatigue resistance of TN could be attributed to surface irregularities, particularly machining grooves. In comparison to ER, TN's surfaces have numerous machining grooves that could initiate and propagate fatigue fractures more readily than ER's smoother surfaces resulting from heat treatment and surface coating [24].

In terms of bending stiffness, PG showed higher stiffness than ER and TN. In other words, ER showed the most flexible properties with low bending stiffness. Therefore, the heat-treated ER exhibits remarkable flexibility even at room temperature, owing to its dominant martensitic property. This is the most important characteristic of the ER file and has not been previously reported. According to the manufacturer (Maruchi), ER was designed to possess soft properties while increasing fracture resistance through patented heat treatment and surface treatment (MT wire technology) [23, 24].

Reddy et al. [36] reported that the cyclic fatigue resistance of TN was significantly higher compared to PG, which contrasts with the results of this study. However, Elnaghy et al. [35] reported that the HyFlex CM instruments (Coltene-Whaledent, Allstetten, Switzerland) had greater fatigue resistance than Vortex Blue (DENTSPLY Tulsa Dental Specialties, Johnson City, TN), TN, and FlexMaster. Although Elnaghy et al. [35] did not compare TN with the PG, similar to this study, TN did not demonstrate the highest fatigue resistance when compared to the HyFlex CM and Vortex Blue. These findings of lower fatigue resistance in TN might be attributed to its lower A*p* temperature (25 °C), which is around room temperature and lower than body temperature.

As discussed above considering the test condition, temperature is an important factor to make differences on the in-vitro fatigue resistance tests. Considering the body temperature, it is important to determine the A*p* temperature of the file alloys. If the file alloy has a lower A*p* temperature than the body temperature, it may not gain any specific advantage from heat treatment. Thus, DSC evaluation is important for assessing the thermal properties of the file alloys.

The effect of phase transition temperature on torsional strength is relatively minimal. This may be primarily due to experimental limitations, as the influence of temperature was only applied to the apical 3 mm of the file during the torsional test. As a result, the full impact of temperature on the entire length of the file could not be accurately assessed. The localized temperature effect on the apical end may not reflect the overall behavior of the file, and further studies with more comprehensive temperature control along the entire length of the file could provide a better understanding of its influence on torsional strength.

In this study, for the torsional resistance test, a rotation speed of 60 rpm was applied, despite the ISO and American Dental Association (ADA) suggesting a speed of 2 rpm [28, 29]. Ha et al. [37] reported that the torsional resistances of the rotary instruments were not affected by the rotational speed. As they described, the ISO and ADA methods are designed to test the mechanical performance of stainless-steel hand files, for which a speed of 2 rpm is reasonable. However, NiTi rotary instruments typically have a much higher recommended rotational speed.

The instruments used in this study for the cyclic fatigue resistance tests were rotated in a pecking motion using an endodontic motor at speeds of 600 rpm, 500 rpm, and 300 rpm for ER, TN, and PG, respectively, following the manufacturer's instructions. Li et al. [38] evaluated cyclic fatigue resistances of rotary files depending on rpm and found that the time to failure significantly decreased as the rotational speeds were increased, although the cycles until fracture were not significantly affected. Therefore, comparing the NCF in this study to assess fatigue resistance would be an appropriate criterion.

Minimally invasive approaches often result in small access cavities, which may lead to a curved or inclined access of the file to the root canals. This situation may increase the difficulty of maintaining straight-line access, and result in higher stress on files due to curvature or angulation, thereby heightened the risk of file fracture or deformation. In such clinical situations, clinicians may select heat-treated files to reduce the risk of file fracture [39].

This study has some limitations because the physical properties of files are influenced not only by heat treatment but also by geometry, such as thickness and cross-sectional shape. Therefore, it is unclear whether the results of this in-vitro experiment were sorely due to heat treatment or geometry. To understand the changes in physical properties resulting from heat treatment,

different heat treatments applied to the files with the same geometry could be performed. Thus, further investigation may consider examining the differences in physical properties resulting from various heat treatment applied to files with identical geometries.

In summary, the file used for minimally invasive root canal preparation is small in size and heat-treated, leading to excellent fatigue fracture resistance. However, it is essential to select the file appropriately based on the specific anatomical conditions of the root canal system and the tooth, such as canal curvature, calcification levels, and access cavity designs. Clinicians should balance the preservation of tooth structure with the mechanical performance requirements of the file to ensure optimal treatment outcomes.

Conclusions

This study compared the torsional fracture resistance, bending stiffness, and cyclic fatigue resistances of heat-treated NiTi files (TruNatomy and EndoRoad) designed for minimally invasive instrumentation with a common heat-treated NiTi instrument system (ProTaper Gold).

Among the tested heat-treated instruments, ProTaper Gold exhibited the highest torsional strength and resistance compared to others. EndoRoad was the most flexible instrument with lower bending stiffness. EndoRoad also showed higher torsional resistance than TruNatomy as a minimally invasive instrument.

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Author contributions
JHH and HCK conceptualized the study. YJK collected the data. YJK and JHH analyzed and interpreted the data. YJK and SWK drafted the manuscript. GG and HCK critically revised the manuscript. All the authors approved the final version for submission and publication.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Human ethics and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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