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Research Article

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Effect of surface treatment on the mechanical properties of nickel-titanium files with a similar cross-section

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ABSTRACT

Objectives: The aim of this study was to compare the mechanical properties of various nickel-titanium (NiTi) files with similar tapers and cross-sectional areas depending on whether they were surface-treated.
Materials and Methods: Three NiTi file systems with a similar convex triangular cross-section and the same ISO #25 tip size were selected for this study: G6 (G6), ProTaper Universal (PTU), and Dia-PT (DPT). To test torsional resistance, 5 mm of the straightened file's tip was fixed between polycarbonate blocks (n = 15/group) and continuous clockwise rotation until fracture was conducted using a customized device. To evaluate cyclic fatigue resistance, files were rotated in an artificial curved canal until fracture in a dynamic mode (n = 15/group). The torsional data were analyzed using 1-way analysis of variance and the Tukey *post-hoc* comparison test, while the cyclic fatigue data were analyzed using the Mann-Whitney *U* test at a significance level of 95%.
Results: PTU showed significantly greater toughness, followed by DPT and G6 ($p < 0.05$). G6 showed the lowest resistance in ultimate torsional strength, while it showed a higher fracture angle than the other files ($p < 0.05$). In the cyclic fatigue test, DPT showed a significantly higher number of cycles to failure than PTU or G6 ($p < 0.05$).
Conclusions: Within the limitations of this study, it can be concluded that the torsional resistance of NiTi files was affected by the cross-sectional area, while the cyclic fatigue resistance of NiTi files was influenced by the surface treatment.

Keywords: Cross-section; Cyclic fatigue; Nickel-titanium file; Surface treatment; Torsional strength

INTRODUCTION

Over the past 2 decades, nickel-titanium (NiTi) rotary instruments have become more popular for root canal treatment, because they have properties that allow them to be more efficient than stainless steel instruments [1-3]. NiTi rotary files are more flexible than stainless steel files, which allow maintenance of the original root canal and a smaller chance of procedural errors [3-5]. However, NiTi rotary instruments have the potential risk of unexpected fracture during use [6,7].

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The 2 main causes of fracture in NiTi instruments are cyclic fatigue and torsional failure [6,7]. The mechanisms of these failure modes are widely known. Cyclic fatigue fracture occurs due to repetitive cycles of tension and compression in a curved canal, while torsional fracture results from torsional overload when the file becomes locked in a canal [8,9]. In clinical situations, fracture usually occurs due to the combination of repetitive cyclic and torsional loads [6].

To overcome the risks of fracture in clinical use, researchers have studied the physical and mechanical properties of NiTi rotary files according to the geometric features, heat treatment of the NiTi alloy, and surface treatment [10-13]. The G6 (Global Top Inc., Goyang, Korea) and Dia-PT (Dia-Dent, Cheongwon, Korea) NiTi file systems have been recently introduced. Both NiTi systems are made of a conventional NiTi alloy and feature a triangular cross-sectional area that is almost idential to that of the ProTaper Universal system (Dentsply Maillefer, Ballaigues, Switzerland). The manufacturers of G6 and Dia-PT claim that a special surface treatment on their file systems reduced the machining marks or grooves on the file's surface, resulting in a slower initiation of fatigue crack or propagation [14,15].

Cyclic fatigue failure of NiTi instruments may occur as a result of stress concentration at a surface defect or irregularity [7,14,15]. The effect of surface treatments on cyclic fatigue resistance has been studied, and cyclic fatigue resistance has been found to be increased by removing surface irregularities [14,15]. However, few studies have investigated the effect of surface treatments on the mechanical properties of NiTi instruments with similar features in terms of cross-sectional design and taper. In particular, limited evidence has been published regarding the mechanical properties of the G6 and Dia-PT files.

Therefore, this study aimed to compare the mechanical properties of various NiTi files with a similar taper and cross-sectional shape depending on the presence of surface treatment.

MATERIALS AND METHODS

Three NiTi file systems were selected for this study: G6 size A2 (G6), ProTaper Universal size F2 (PTU), and Dia-PT size D4 (DPT). These systems have a similar convex triangular cross-section and the same ISO #25 tip size. G6 and DPT are made of a conventional NiTi alloy with a surface treatment, and PTU was selected as a control group without a surface treatment. Before the test, all the files were inspected under a stereoscope. New instruments with surface defects were discarded.

Forty-five files were used for the torsional resistance test ($n = 15$ for each group). The test was conducted using a customized device (AEndoS, DMJ system, Busan, Korea; **Figure 1A**). A 5-mm length of the straightened file's tip was fixed between polycarbonate blocks to exclude lateral vector forces. The rotation speed was set at 2 rpm in a continuous clockwise direction until a fracture occurred [15]. The torsional load (N·cm) and distortion angle were recorded during rotation. The data were stored at the rate of 50 Hz and extracted to create a stress-strain curve for each file. The toughness and ultimate torsional strength were automatically calculated using software (Origin 6.0, Microcal Software Inc., Northampton, MA, USA).

The 45 other new files were used for the cyclic fatigue resistance test ($n = 15$ for each group). Using a custom-made device (EndoC, DMJ system), each NiTi file was rotated with a repeated

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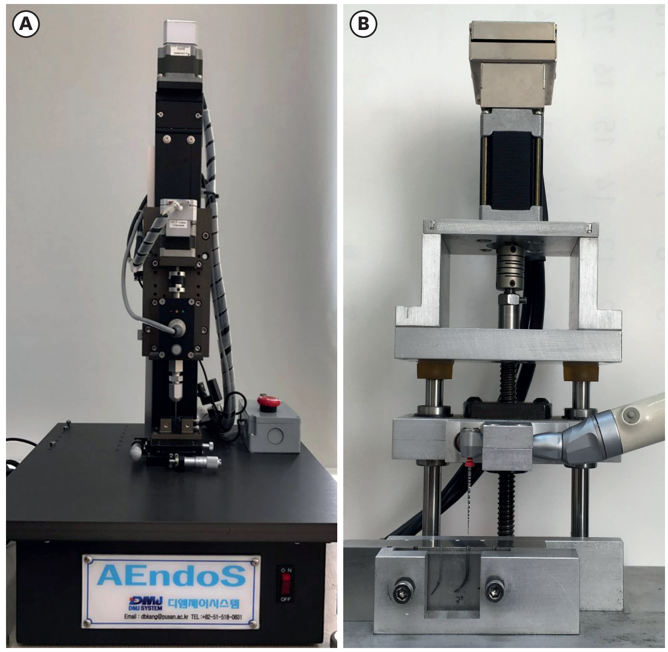

Figure 1. Customized test devices used in this study. (A) A test device for the torsional test (AEndoS, DMJ system, Busan, Korea); (B) A test device for the cyclic fatigue test (EndoC, DMJ system).

up-and-down movement in a curved canal (**Figure 1B**). The artificial tempered steel canal was fabricated with a length of 17 mm, a radius of 6 mm, and a 35° angle of curvature [16,17]. Before each test, synthetic oil (WD-40, WD-40 Company, San Diego, CA, USA) was sprayed in the canal to reduce the frictional stress between the canal wall and the NiTi file. The cyclic fatigue test was done in a dynamic mode to simulate a clinical situation. The settings for the test included a displacement of 4 mm in each direction per 0.5 seconds and 50 milliseconds of dwell time. The file was freely rotated in the canal at a constant speed of 300 rpm using a torque-controlled motor (X-smart™, Dentsply Maillefer). Time until fracture was recorded, and the time was converted into number of cycles to failure (NCF). The length of the fractured fragment was measured by a digital microcaliper (Mitutoyo, Kawasaki, Japan).

After the tests, the cross-sectional and longitudinal aspects of the fractured instruments in each group were examined under a scanning electron microscope (SEM; S-4800 II, Hitachi High Technologies, Pleasanton, CA, USA) to see the topographic features of the fractured surface.

The data were analyzed using the Kolmogorov-Smirnov test to check the assumption of normality. The data from the torsional resistance test showed a normal distribution, so the data were analyzed using 1-way analysis of variance and the Tukey *post-hoc* comparison test, while the data from the cyclic fatigue test were analyzed using the Mann-Whitney *U* test. The significance level was set at the level of 95%. All statistical analyses were performed using the SPSS 15.0 software (SPSS Inc., Chicago, IL, USA).

RESULTS

The torsional and cyclic fatigue resistance of each NiTi instrument are presented in **Table 1**. PTU showed significantly greater toughness, followed by DPT and G6 ($p < 0.05$). G6 showed

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Table 1. Torsional and cyclic fatigue resistance of the tested NiTi files

Group	Torsional resistance			Cyclic fatigue resistance	
	Fracture angle (°)	Ultimate strength (N·cm)	Toughness (N·cm°)	NCF	Fragment length (mm)
DPT	511 ± 60[a]	2.89 ± 0.38[b]	1,140 ± 147[b]	1,134 ± 246[b]	2.91 ± 0.41
PTU	543 ± 57[a,b]	3.08 ± 0.38[b]	1,333 ± 183[c]	842 ± 59[a]	2.53 ± 0.53
G6	594 ± 90[b]	2.13 ± 0.13[a]	974 ± 148[a]	944 ± 123[a]	2.96 ± 1.51

NiTi, nickel-titanium; NCF, number of cycles to failure; DPT, Dia-PT NiTi file system (Dia-Dent, Cheongwon, Korea); PTU, ProTaper Universal NiTi file system (Dentsply Maillefer, Ballaigues, Switzerland); G6, G6 NiTi file system (Global Top Inc., Goyang, Korea).
[a,b,c]Different superscripts indicate significant differences between groups ($p < 0.05$).

the lowest resistance in ultimate torsional strength, while it showed a greater fracture angle than the other files ($p < 0.05$). In the cyclic fatigue test, DPT showed a significantly higher NCF than PTU and G6 ($p < 0.05$).

SEM images revealed the typical features of torsional and cyclic fatigue failure on each fractured surface (**Figures 2** and **3**). The cross-sectional image of each NiTi file system showed a similar convex triangular shape. In the longitudinal surfaces of each SEM image, the surface-treated G6 and DPT showed a smooth surface, while PTU showed machining grooves on the surface.

DISCUSSION

Despite the efforts to reduce the fracture rate of NiTi files, file fracture remains one of the major reasons for which clinicians are afraid of using NiTi files. An irremovable fractured fragment may block the canal and negatively affect the clinical outcome [18,19]. Therefore, it is important to prevent file fractures and to investigate the fracture resistance of newly introduced NiTi files.

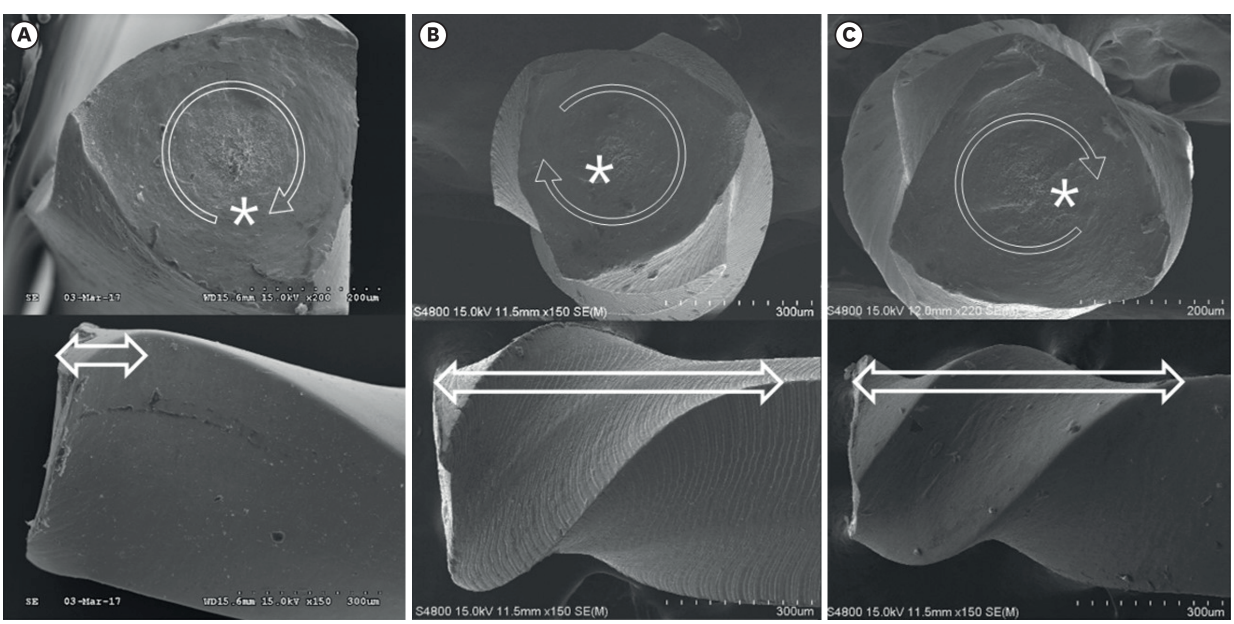

Figure 2. Scanning electron micrographs of the fractured surface after the torsional fracture test. (A) Dia-PT nickel-titanium file system (DPT; Dia-Dent, Cheongwon, Korea); (B) ProTaper Universal nickel-titanium file system (PTU; Dentsply Maillefer, Ballaigues, Switzerland); (C) G6 nickel-titanium file system (G6; Global Top Inc., Goyang, Korea). Cross-sectional aspects of all groups revealed the typical features of torsional fractures, such as concentric abrasion marks (circular arrow) and fibrous dimples (asterisk) from the torsional center. In the lateral aspects, the DPT and G6 groups showed a smooth surface, while PTU showed many machining grooves. The arrows on the lateral aspects indicate unwound distortion areas with a reverse helix.

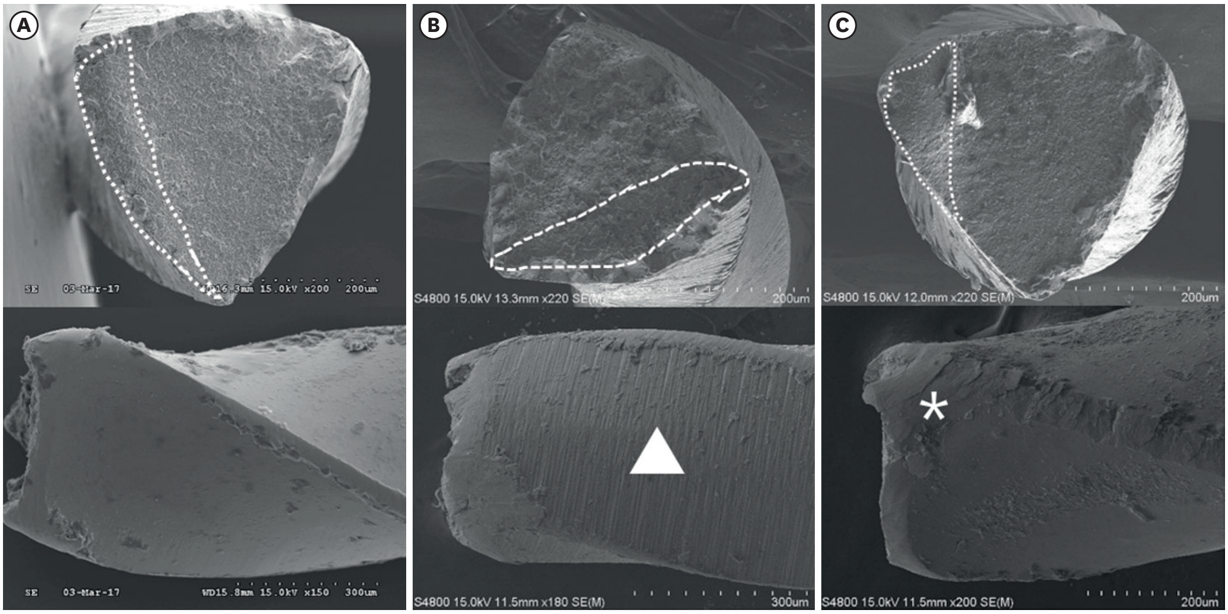

Figure 3. Scanning electron micrographs of the fractured specimens after the cyclic fatigue test. (A) Dia-PT nickel-titanium file system (DPT; Dia-Dent, Cheongwon, Korea); (B) ProTaper Universal nickel-titanium PTU (Dentsply Maillefer, Ballaigues, Switzerland); (C) G6 nickel-titanium file system (G6; Global Top Inc., Goyang, Korea). Cross-sectional aspects of all groups revealed the typical features of cyclic fatigue fracture such as crack initiation area and fibrous fast fracture zone (dotted area). In the lateral aspects, the PTU group showed multiple machining grooves (white triangle), while the other groups showed smooth surfaces. Micro-cracks were shown (asterisk) near the fracture area from the group G6.

Several factors, such as cross-sectional design, the chemical composition of the alloy, and the thermo-mechanical process during manufacturing, affect the torsional behavior of NiTi rotary files [15,20-22]. In this study, PTU showed significantly greater toughness and ultimate strength. It has been reported that increased cross-sectional area can improve the torsional resistance of NiTi files [23]. To measure the cross-sectional area, SEM images of each system at D5 were taken and the area was calculated using ImageJ software (http://rsbweb.nih.gov/ij, National Institutes of Health, Bethesda, MD, USA). PTU was found to have the largest area (mean area: 150,280 μm^2), followed by DPT (mean area: 144,107 μm^2) and G6 (mean area: 114,987 μm^2). According to the manufacturers of the tested file systems, PTU and G6 have a taper of 0.08 at the tip, while DPT has a taper of 0.05. Assuming that the 3 NiTi files had same size of #25 at the tip, the cross-sectional area at D5 should have been similar in PTU and G6. Because the 3 tested NiTi files were made of a conventional austenite 55-NiTi alloy, the present results may have primarily resulted from their different cross-sectional areas.

The cyclic fatigue test revealed that DPT showed the highest NCF, followed by G6 and PTU. The factors influencing the cyclic fatigue of NiTi file include file design, instrument technique, and canal anatomy [6,24-26]. It was reported that cyclic fatigue resistance was primarily affected by the design of NiTi files, rather than the electropolishing on the surface [26]. In this study, because other conditions such as instrument technique and canal anatomy were held constant, the file design may have affected the result. The cross-sectional shape of the 3 NiTi file systems was similar, but the taper of DPT was smaller than that of the other 2 files. DPT has a taper of 0.05 from the tip, while A6 and PTU have a taper of 0.08 according to their manuals. Therefore, DPT should theoretically have been more resistant to cyclic fatigue than the other NiTi files, because a smaller-taper NiTi file would be expected to be more flexible. However, considering the broad standard deviation in the DPT group, the

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reliability of this file system may have limitations with regard to obtaining similar cyclic fatigue resistance results. In the SEM evaluation, PTU showed a rough surface with many machined grooves. In contrast, DPT and A6 showed surfaces that had been smoothed by their companies' polishing techniques. The manufacturing process may have contributed to the propagation of fractures [27]. Initiation of a fatigue crack normally occurs at the outer surface of the instrument. The stresses generated during instrumentation concentrated on a machining groove may cause rapid crack propagation. Furthermore, the multitude of machining grooves on the instrument surface as a result of the grinding process may lead to crack initiation at multiple locations [28]. Although the manufacturer of DPT and A6 have not revealed the details of the surface treatment technique, electropolishing is a surface treatment method that is controlled by a chemomechanical process and is used to remove surface defects. In a previous study, NiTi files after surface treatment were more resistant to cyclic fatigue than the same files without surface treatment [29]. Electropolished NiTi files showed superior clinical performance due to a reduction of the micro-cracks on the surface, which are able to be either the starting points of crack initiation or residual stress points [14,28,30].

CONCLUSIONS

Within the limitations of this study, it was concluded that the torsional resistance of NiTi files was affected by the cross-sectional area, while the cyclic fatigue resistance of NiTi files was influenced by the surface treatment. A smoothed surface, from which machining defects were removed, increased the cyclic fatigue life of the instruments.

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