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ORIGINAL ARTICLE

# The geometric effect of an off-centered cross-section on nickel–titanium rotary instruments: A finite element analysis study

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**Abstract** *Background/purpose:* Geometric design dictates the mechanical performance of nickel–titanium rotary instruments. Using finite element (FE) analysis, this study evaluated the effects of an off-centered cross-sectional design on the stiffness and stress distribution of nickel–titanium rotary instruments.
*Materials and methods:* We constructed three-dimensional FE models, using ProTaper-NEXT type design (PTN) as well as three other virtual instruments with varied cross-sectional aspect ratios but all with the same cross-sectional area. The cross-sectional aspect ratio of the PTN was 0.75, while others were assigned to have ratios of 1.0 (square), 1.5 (rectangle), and 2.215 (centered-rectangle). The PTN center of the cross-section was '$k$', while others were designed to have $0.9992k$, $0.7k$, and 0 for the square, rectangle, and centered-rectangle models, respectively. To compare the stiffness of the four FE models, we numerically analyzed their mechanical response under bending and torque.
*Results:* Under the bending condition, the square model was found to be the stiffest, followed by the PTN, rectangle, and then the centered-rectangle model. Under the torsion, the square model had the smallest distortion angle, while the rectangular model had the highest distortion angle.

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*Conclusion:* Under the limitation of this study, the PTN type off-centered cross-sectional design appeared the most optimal configuration among the tested designs for high bending stiffness with cutting efficiency while rotational stiffness remained similar with the other designs.


## Introduction

Various kinds of nickel–titanium (Ni-Ti) systems have been introduced into the market. Over 2 decades, the development and innovations in the design of rotary Ni-Ti instruments has led to new concepts in design and metal alloys.[1–3] Despite these advancements, the fracture of Ni-Ti instruments remains a hot topic due to the nature of its use in endodontic procedures.[4,5]

During a session of root canal enlargement, the instrument is exposed to various levels of stress or strain, which can lead to plastic deformation and the generation of internal residual stress within the instrument. Accumulation of internal residual stress and damage can subsequently result in instrument fracture. The degree of accumulating damage varies depending on the geometric design of the instrument and the forces exerted on the root dentin may jeopardize its integrity.[6,7]

The manufacturing process of Ni-Ti instruments, which includes heat treatment and methods used to realize the geometric shapes, fundamentally determines their mechanical properties.[8–10] Design elements of Ni-Ti instruments have been widely investigated by testing cyclic fatigue and torsional resistances or using finite element (FE) analysis to create controlled conditions.[11,12] It has been demonstrated that the pitch, cross-sectional shape and area determine the flexibility and torsional resistance of the instruments.[11,12]

In the majority of conventional Ni-Ti files, the rotational axis corresponds to the geometric cross-sectional center. An off-centered cross-sectional design was first introduced by Micro-Mega (Besançon, France) in their Revo-S system. More recently, another off-centered cross-sectional design was introduced as the ProTaper Next (PTN; Dentsply Maillefer, Ballaigues, Switzerland). The geometric cross-sectional centers of these instruments are displaced from the instruments' centers of rotation. The manufacturers claim that, compared to conventional concentric instrument designs, the off-centered cross-sectional design creates a snake-like, swaggering movement of the instrument that reduces the stress generation during rotation and screw-in forces by decreasing the instrument's contacts with the tooth's canal wall, while still increasing the space needed for debris removal.[13,14] Current available studies of off-centered design have experimentally examined mechanical performances, such as cyclic fatigue resistance and torsional resistance against fractures.[13,15] However, to the best of our knowledge, no studies have been published that analyzed the effects of off-centered designs on the deformation and stress patterns in the instrument.

The aim of this study was to evaluate systematically the fundamental effects of the off-centered cross-sections on deformations and stresses in Ni-Ti rotary instruments under controlled conditions provided by FE analysis.

## Materials and methods

Four different generalized geometric designs were investigated (Figure 1). The PTN model had the same cross-sectional shape and off-set as ProTaper Next instruments. All four designs had the same cross-sectional area but with different cross-sectional shapes and aspect ratios. The cross-section of PTN was rectangular, with an aspect ratio of 0.75. The degree to which models were off-centered was expressed with respect to the offset $k$ of PTN. The other three models were: (1) square (EXP1-SQ; aspect ratio = 1.00 / an off-center = 0.9992$k$); (2) rectangle (EXP2-RT; aspect ratio = 1.50 / an off-center = 0.7$k$); and (3) centered-rectangle (EXP3-CR; aspect ratio = 2.215 / an off-center = 0). All instrument models had the same 16-mm long working part and the same external peripheral diameter (1 mm at D16, 0.30 mm at D0). The models were meshed for the FEA with 8-noded hexahedral elements using I-DEAS, version 5 (Siemens PLM Software, Cypress, CA, USA). The final FE models of the PTN consisted of 7104 elements with 9234 nodes. The square design (EXP1-SQ) consisted of 9728 elements with 6909 nodes. The rectangular design (EXP2-RT) consisted of 6624 elements with 10,200 nodes. The centered-rectangle design (EXP3-CR) consisted of 4640 elements with 6660 nodes.

We performed numerical analysis using ABAQUS V6.10-1 (SIMULIA, Providence, RI, USA) to determine the mechanical response and stress distributions in the modeled instrument designs under bending and torsion. The instruments' material properties were modeled using the stress–strain relationship described by Liu.[16] Modulus of elasticity of the austenite phase, the critical stress at the beginning of the transformation to the R-phase, and the Poisson's ratio were 23.5 GPa, 450 MPa, and 0.33 respectively.[17]

Flexural stiffness was calculated as the ratio of bending load and loading point deflection. In this study, the instrument tip was displaced 2 mm. Stresses in each integration point were recorded at each rotation angle during the rotation of 90° considering the symmetry of cross-section (Figure 1E). For the torsional condition, the file was fixed at 4-mm length of the tip, while the file was rotated using a torsional moment of 2.5 Nmm at the end of the shaft (Figure 1F). Reaction force at the file tip was recorded during flexure and distortion angle during torsion.

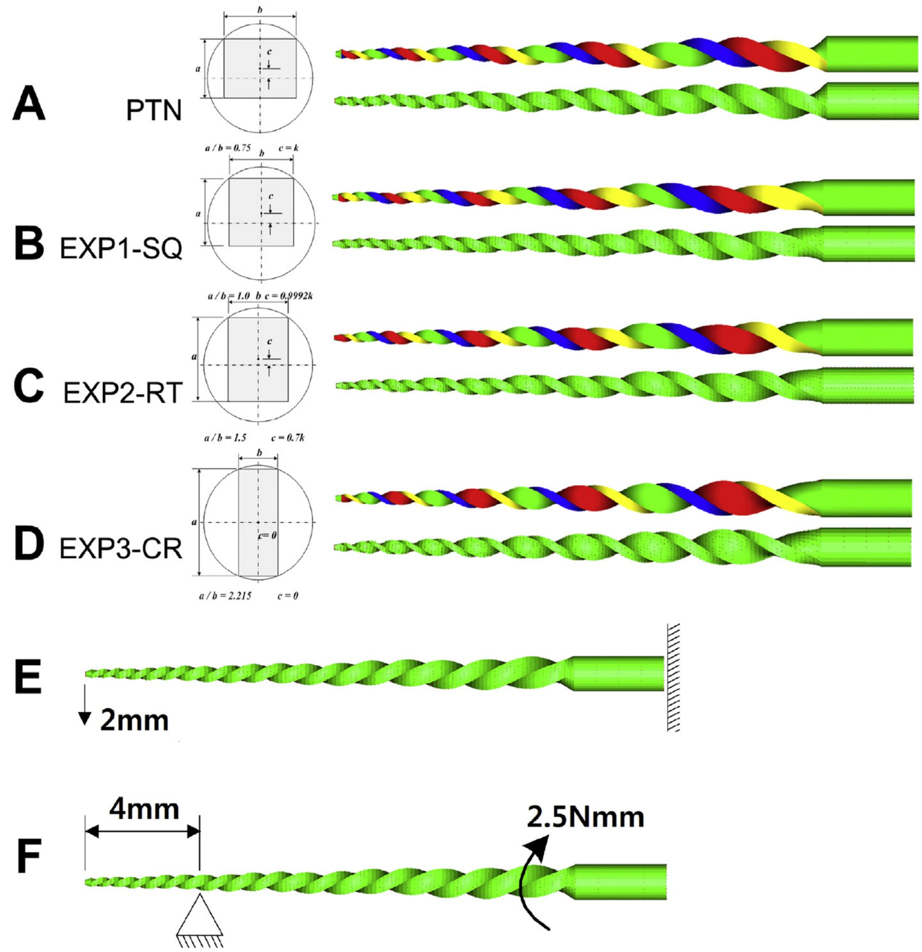


**Figure 1** Four different geometric designs were evaluated using finite element analysis. (A) ProTaper-NEXT type design (PTN); aspect ratio = 0.75, off-center = *k*. (B) Square (EXP1-SQ); aspect ratio = 1.00, off-center = 0.9992*k*. (C) Rectangle (EXP2-RT); aspect ratio = 1.50, off-center = 0.7*k*. (D) Centered-rectangle (EXP3-CR); aspect ratio = 2.215, off-center = 0. (E) Simulated flexural stiffness test. (F) Simulated torsional stiffness test.

Additionally, the stresses in the file models were recorded represented by the von Mises equivalent stresses.

## Results

Under the bending condition, Figure 2A–D shows the stress distribution along the instrument. The centered-rectangle model EXP3-CR showed the lowest stress during bending condition and the PTN model had the relatively lower stress generation than other off-centered models. The bending stiffness (N/mm) of the PTN, EXP1, EXP2, and EXP3 models were calculated from the reaction force at the instrument tip divided by the tip displacement (Table 1). Figure 2E shows the instrument bending stiffness graphically, represented by the slope of the curves. The model with a square cross-section (EXP1-SQ) and a 0.9992*k* off-center design showed the greatest stiffness, followed by, in descending order, PTN (aspect ratio = 0.75 / off-center = *k*), rectangle model EXP2-RT (aspect ratio = 1.50 / an off-center = 0.7*k*), and centered-rectangle model EXP3-CR (aspect ratio = 2.215 / an off-center = 0).

Under the torsion condition, Figure 3 shows the stress distribution along the instrument over the clamped level and at the cross-sections. The von Mises stresses in a representative cross-section during torque application are shown in Figure 3(cross sections). For all instrument models, regardless of how much it was off-centered, the highest torsional stresses (about 300–450 MPa; green and yellow colors in the scale) were concentrated at the center of long side of the instruments' cross-section near the rotation center while the lowest stresses were at the center of the cross-sections (0 MPa; dark blue colors in the scale). Figure 3E shows the distortion angles due to applied torque. The models did not show a significant difference. The slopes of the curves represent the torsional stiffness. The steepest distortion–torque slope was found for the model with the square cross-section (EXP1-SQ), which indicates that it had the highest torsional stiffness among the four designs. The rectangle model (EXP2-RT) had the lowest torsional stiffness. The PTN model had higher torsional stiffness than the EXP2-RT.

## Discussion

The research and development of Ni-Ti rotary instruments have continued for over 2 decades in order to achieve the

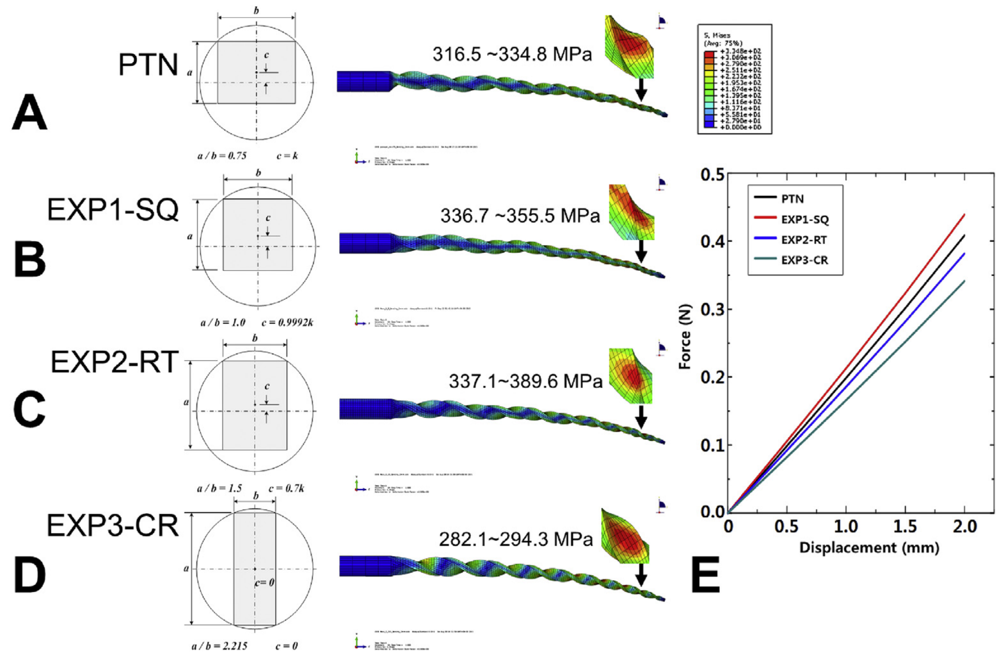


**Figure 2** Comparison of stress distribution and calculated bending stiffness of the four instrument models. (A—D) Maximum stresses were concentrated at the 3.2 mm level from the tip (arrow indicated). The ProTaper-NEXT type design (PTN) model had lower stress generation than other off-centered models, while the centered-rectangle (EXP3-CR) model had the least stress. (E) The PTN model showed less bending stiffness than the square (EXP1-SQ) model.

**Table 1** Bending stiffness (N/mm) and torsional stiffness (N mm/°) of the simulated finite element instrument models with various off-centered cross-sections.

| Models | PTN | EXP1-SQ | EXP2-RT | EXP3-CR |
|---|---|---|---|---|
| *Off-center* | *k* | 0.9992*k* | 0.7*k* | 0 |
| *Aspect ratio (a/b)* | 0.75 | 1.0 | 1.5 | 2.215 |
| Bending stiffness (N/mm)* | 0.204—0.209 | 0.218—0.219 | 0.191—0.197 | 0.163—0.179 |
| Torsional stiffness** (N·mm/°) | 0.190 | 0.196 | 0.187 | 0.192 |

*: range at different file rotation angles. **: at 4-mm-length of the tip.
EXP1-SQ = square; EXP2-RT = rectangle; EXP3-CR = centered-rectangle; PTN = ProTaper-NEXT type design.

highest clinical efficiency and promote safety by preventing file fractures. Modifications to Ni-Ti rotary instruments have involved metallurgical alteration, manipulating the kinetics of the instrument, and improvement in design.[10,15,18—23] The change from conventional Ni-Ti alloy to M-wire, R-phase heat treatment, and controlled memory (CM) wire has been made in order to enhance mechanical performance. Geometric innovations contribute to improving the cutting efficiency and fracture resistance of the instrument.[6,24] One of the more recent innovations is the off-centered cross-sectional design that has been incorporated into the Revo-S (Micro-Mega) and ProTaper Next. Manufacturers claim that this off-centered cross-sectional design changes the instruments' mechanical responses to a *snake-like movement* or *swaggering movement*. This change enhances clinical performance, for example, reducing screw-in force and increasing debris removal. How off-centering affects the stiffness and stress characteristics has to our knowledge not yet been studied.

Superior mechanical properties have been reported for off-centered PTN instruments compared to instruments that have conventionally centered cross-sectional designs.[15,25,26] However, those studies compared files with completely different shapes and different alloys. Although those tests offer valuable insight into the mechanical performance of specific instruments, the geometric factor of the off-center design cannot be independently studied in such tests. In this study we used numerical analysis to isolate off-center design features without confounding factors. Numerical analysis is a widely used and proven method to study mechanical stresses and strains, and have also been successfully used and validated for endodontic instruments.[24,27] We tested four different FE models designed to evaluate the *off-center* effect. All conditions (such as loading, material properties, instrument dimensions, and cross-sectional areas) were the same among these models, they only varied in cross-sectional shape and centering. For our study, we exposed these models to

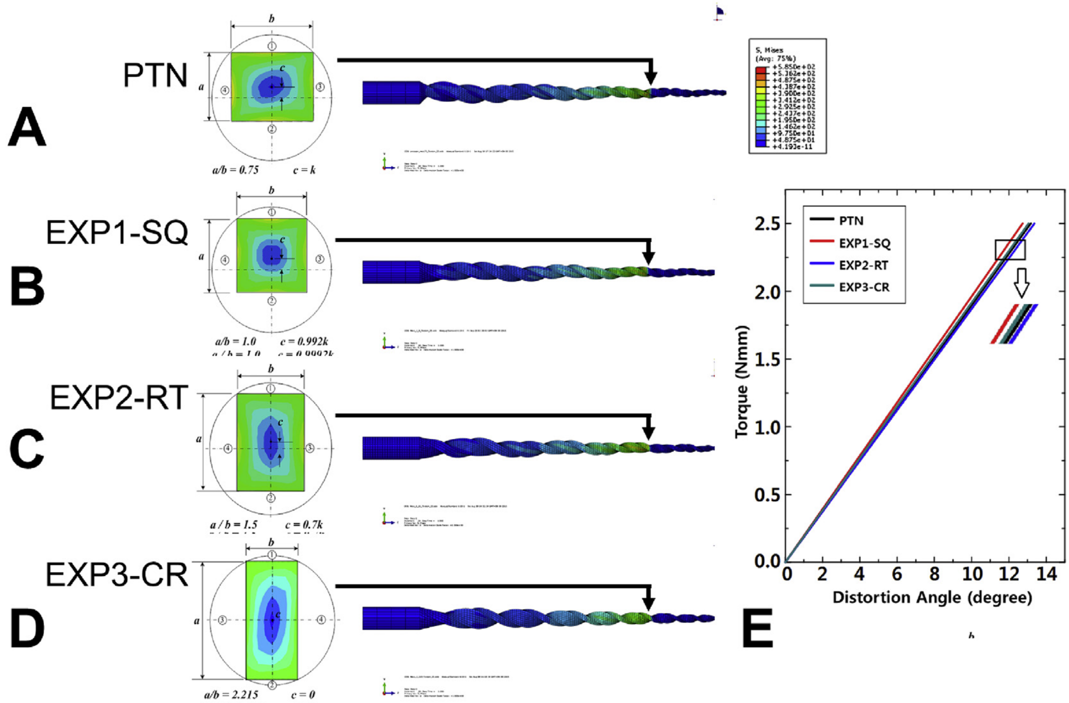


**Figure 3** Comparison of stress distribution and calculated torsional stiffness of the four instrument models. (A to D) During torsion, the highest stresses were at the center of long side near the rotation center. The ProTaper-NEXT type design (PTN) and square (EXP1-SQ) models have the highest stress concentration at side ②, while rectangle (EXP2-RT) and centered-rectangle (EXP3-CR) models have similarly high stresses at sides ③ and ④. (E) PTN model had higher torsional stiffness than the EXP2-RT.

simulated flexural and torsional conditions as instruments undergo during root canal preparation. Simulated tests showed that the PTN design (aspect ratio = 0.75 / an off-center = *k*) had higher stiffness than the rectangle model, EXP2-RT (aspect ratio = 1.50 / an off-center = 0.7*k*), and the centered-rectangle model, EXP3-CR (aspect ratio = 2.215 / an off-center = 0). The PTN model also had greater torsional stiffness than the EXP2-RT. The degree of stiffness was not consistently related to the degree by which the cross-section was off-center. These results are in accordance with the findings of prior studies that have shown that flexural and torsional stiffness are dependent on cross-sectional geometry and that the stiffness was inversely proportional to the area moment of inertia.[7,11,28]

In the present study, while maintaining the same cross-sectional area, the aspect ratios were determined by the extent to which it was off-center. Among the three rectangle-based models except the square in this study, the bending flexibility was decreased as the off-center distance was increased (Figure 2E). The PTN was shown to have lower torsional stiffness than the square and centered rectangle models and a higher resistance to bending than the rectangle model. Because the PTN had the greatest bending stiffness amongst the rectangle-based models except the square model and the variation in rotational stiffness among the four models was small, the PTN type design can be expected to generate enough forces for cutting as well as advancing to the apical foramen. This supports the evidence that a PTN type design is good for clinical use.[6,29,30]

In conclusion, FE analysis was used to systematically evaluate the effect of an off-center design on the mechanical responses of Ni-Ti rotary instruments. Among various design options, the PTN based off-center design was found to be the most optimized to deliver flexural responses that are clinically desirable. Further research will be needed to evaluate the mechanical performance during rotation inside root canal lumen.

## Conflicts of interest

The authors have no conflicts of interest relevant to this article.

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