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ProTaper rotary root canal preparation: assessment of torque and force in relation to canal anatomy

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Abstract

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Aim To investigate physical parameters for ProTaper nickel–titanium (NiTi) rotary instruments whilst preparing curved canals in maxillary molars *in vitro*.

Methodology A novel torque-testing platform was used to prepare root canals in 15 extracted human maxillary molars with ProTaper rotary instruments. Peak torque and force was registered along with numbers of rotations required to shape the canals. Canals were divided into 'wide' and 'constricted' groups depending on canal volumes assessed by micro computed tomography. Mean scores for each instrument type were calculated and statistically compared using ANOVA and Scheffé posthoc tests.

Results Mean torque varied between 0.8 ± 0.5 and 2.2 ± 1.4 N cm whilst mean force ranged from 4.6 ± 2.6 to 6.2 ± 2.7 N. Mean numbers of rotations totalled up to 21. All three variables registered were significantly correlated to preoperative canal volumes ($P < 0.001$) and differed significantly between 'wide' and 'constricted' canals ($P < 0.001$).

Conclusions Whilst high forces were used in some cases, no ProTaper instrument fractured when a patent glide path was present. There were significant positive correlations between canal geometry and physical parameters during shaping.

Keywords: cyclic fatigue, force, ProTaper, torque.

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Introduction

It is generally believed that engine-driven or manually used nickel–titanium (NiTi) instruments produce better-prepared root canals than their stainless steel counterparts. Clinically, however, such instruments, and in particular the rotary types, do have a higher risk of separation (Barbakow & Lutz 1997). Reasons for separation of rotary NiTi instruments include variations in canal anatomy, such as merging, curving, re-curving, dilacerating or dividing canals (Ruddle 2002). Specifically, retrospective analysis of routinely discarded NiTi instruments indicated two distinct fracture mechanisms, namely, torsional and flexural fractures (Sattapan *et al.* 2000a).

Both of these mechanisms may contribute, albeit not uniformly, to instrument separation. Smaller instruments may become wedged into constricted canal areas producing a so-called 'taper lock' effect. The torque required to rotate the shaft of 'taper locked' instrument may exceed the alloy's torsional limit, leading to separation of a relatively small portion of the instrument tip (Sattapan *et al.* 2000a). On the other hand, continuous rotation of files in curved root canals requires the instrument to flex during every rotation, resulting in cyclic compression and elongation, which produces metal fatigue. Fatigue fractures typically occur at the crescent of any given curve, resulting in fragments of various lengths (Sattapan *et al.* 2000a). Unfortunately, both mechanisms have one major fact in common,

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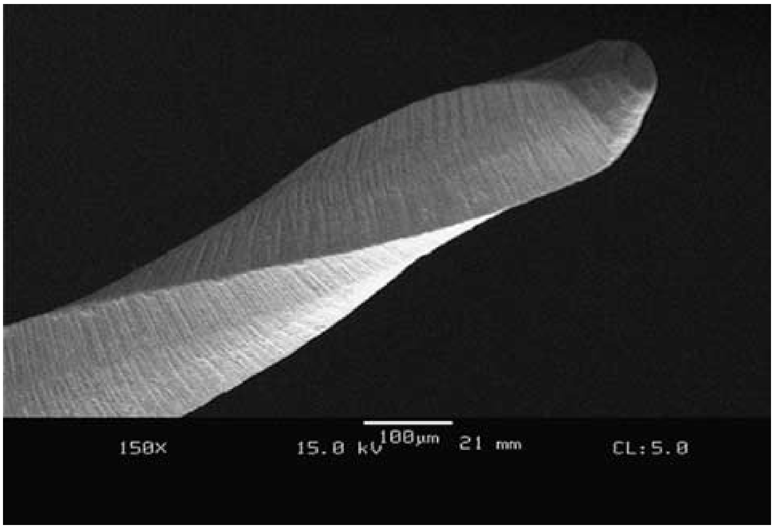

Figure 1 Scanning electron micrograph of ProTaper shaping file 1 detailing the instrument tip and the nonlanded cross-section (original magnification ×150).

that is, they are difficult, if not impossible, to predict clinically.

Manufacturers and clinicians have recommended discarding rotary instruments on a regular basis, e.g. after 10 canals (Yared *et al.* 2001, 2002), or even to consider them as single-use items to avoid cyclic fatigue. Other suggestions to avoid cyclic fatigue include limiting the use of rotary instruments whilst shaping root canals to between 10 or 20 s and not to remain in a canal once a certain working length has been reached (Ruddle 2002). In addition, torque-controlled electrical motors have been marketed recently to help clinicians to better identify when torsional limits are reached (Gambarini 2000). Another method to reduce torsional fracture is to modify the rotary instrument's cross-sectional geometry, thereby increasing cutting efficiency and consequently reducing contact areas and torsional loads (Blum *et al.* 1999a). This concept has resulted in marketing of new instrument types (e.g. ProTaper, Dentsply Maillefer, Ballaigues, Switzerland; FlexMaster, VDW, Munich, Germany), which are claimed to generate lower torque values. In particular, a nonradial landed and more effectively cutting cross-section has been designed for that purpose (Fig. 1).

It is difficult to objectively analyse torsional loads and other physical parameters during preparation of curved canals due to underlying engineering principles (Peters & Barbakow 2002). Indeed, few reports have appeared detailing torque and force during rotary preparation of curved canals. Moreover, it has been suggested that canal geometry might influence rotary instrument performance in terms of shaping outcomes (Nagy *et al.* 1997, Peters *et al.* 2001).

Therefore, the aim of this study as a part of an ongoing project was to investigate torque and force generated by ProTaper instruments when curved canals in extracted maxillary molars were prepared. The effect of canal anatomy on physical parameters was also tested.

Materials and methods

Construction of torque testing platform

Figure 2 details the components of the measurement assembly, which is described in detail elsewhere (Peters & Barbakow 2002). In brief, specimens are secured into a rigid holder attached to a strain gauge, which is in turn connected to a preamplifier (A&D 30, Orientec, Tokyo, Japan). The holder is constructed in a way to allow lateral movement to adjust for various canal orifice positions.

A torque sensor (MTTRA 2, with amplifier Microtest, both Microtec Systems, Villingen, Germany) and a motor (Type ZSS, Phytron, Gröbenzell, Germany) are mounted on a stable metal platform, which moves along a low-friction guide rail for a width of approximately 5 cm. A linear potentiometer (Lp-100, Midori, Osaka, Japan) is attached to the sliding platform to record linear movements.

Data for torque, force and insertion depth were acquired from the sensors via three analogue channels using a 12-bit interface (PCI-MIO-16XE, National Instruments, Austin, TX, USA) using the ENDOTEST software package, which was specifically written for that purpose. Sensors were calibrated regularly using precision-made levers and a set of brass weights of 1–400 g according

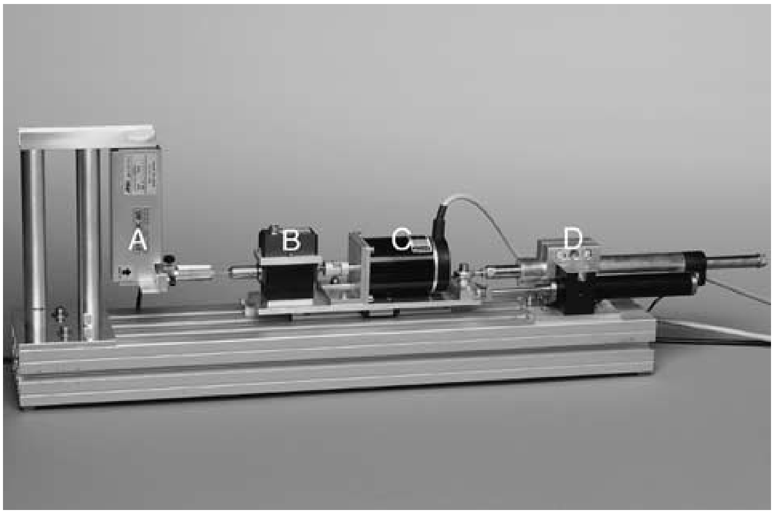

Figure 2 Construction of the torque testing device showing major components (A) force gauge, (B) torque sensor, (C) motor, and (D) linear drive.

to guidelines listed by the respective manufacturers. Variables recorded during each measurement were registered as Newton centimetres, Newton and millimetres, respectively, for torque, force and distance of canal preparation and were stored for subsequent off-line analyses.

In this study, manual feed was used to prepare canals in extracted human maxillary molars and data were recorded at a sampling rate of 100 Hz. In addition to torque and force, the numbers of rotations were counted under the condition that torque exceeded a preset threshold of 0.01 N cm. This threshold was determined from preliminary experiments in order to exclude noise and count only rotations when the canal walls were actually contacted by the rotating instrument.

Preparation of specimens

Fifteen three-rooted maxillary molars were selected from a pool of extracted teeth and stored in 0.1% thymol solution until used. These specimens were mounted on SEM stubs (014001-T, Balzers Union AG, Balzers, Liechtenstein, Germany) and then scanned before and after preparation in a micro computed tomography system (μCT-20, Scanco Medical, Bassersdorf, Switzerland) at 36 μm resolution to metrically determine canal morphology using previously established criteria (Peters *et al.* 2001).

A total of 45 root canals were then prepared using 15 sets of ProTaper instruments, which consist of shaping files 1 and 2 (S1 & S2) and finishing files 1–3 (F1–F3). Shaper X instruments were not available during the course of the study. Rotational speed was preset to 250 r.p.m. using the ENDOTEST software and canals were shaped by an endodontist (C.I.P.) with expertise in rotary techniques and after a training period with ProTaper instruments. Working lengths (WLs) were established by subtracting 0.5 mm from the length of a size 010 stainless steel K-File (Dentsply Maillefer), which was just visible at the main apical foramen. Digital radiographs (Digora, Soredex, Helsinki, Finland) were exposed to verify file position and explore canal anatomy. Canal orifices were enlarged with size 3 and 2 Gates–Glidden burs (Dentsply Maillefer) and pulp chambers were irrigated with 5 mL of tap water. Then, apical preparation was initiated with a size 015 stainless steel K-Flexofiles (Dentsply Maillefer), using Glyde (Dentsply Maillefer) as a lubricant. Four S1 files separated during pilot studies and it was decided to work a size 015 file loose to WL prior to using ProTaper shaping files to establish a glide path for the ensuing rotary preparation.

Canals were subsequently enlarged with S1 and S2, which were used in a gentle pumping and brushing action as recommended by the manufacturer. Mesiobuccal (mb) and distobuccal (db) canals were prepared to an F2 instrument (D1 diameter 0.25 mm) whilst palatal (p) canals were shaped to an F3 instrument (D1 diameter 0.3 mm). Tap water, delivered after each instrument, through a 27-gauge needle acted as the irrigant and new sets of ProTaper instruments were used for every specimen (three canals).

Statistics

A total of 45 root canals in 15 maxillary molars were analysed during shaping procedures. Maximum torques and forces as well as numbers of rotations were calculated for the five tested instruments and were expressed as mean ± SD. When appropriate, Pearson correlation coefficients were calculated to determine relationships between canal anatomy and physical parameters. Furthermore, based on an overall median canal volume of 2.94 mm^3 (mean volume: 3.68 ± 2.29 mm^3) determined by micro computed tomography, 11 of 15 specimens (32 canals) were divided into 'wide' (mean volume: 5.54 ± 2.04 mm^3) and 'constricted' (mean volume: 2.03 ± 0.66 mm^3) groups.

Means in subgroups were statistically contrasted using one- and two-way ANOVAs with Scheffé tests for posthoc comparisons. A level of $P < 0.05$ was considered significant.

Results

A total of 195 records were produced whilst preparing the 45 root canals in maxillary molars *in vitro*. The results showed a distinct relationship between torque, force and instrument insertion depth (Fig. 3). ProTaper instruments were advanced into root canals in a graded oscillating manner and each oscillation produced paralleling increases in apically directed force and torque. However, a phase shift occurred between the two latter variables at approximately 200 ms initially, but this time lag decreased to almost zero when WL was approached (Fig. 3). Overall, there was a highly significant positive correlation between applied force and generated torque ($r = 0.70$, $P < 0.0001$).

Torques

Peak torque scores ranged from 0.1 to 5.4 N cm, with the lowest and highest mean scores generated by S2 and F3 instruments, respectively. Mean torque scores varied significantly between the five tested ProTaper instruments and are listed in Table 1. No significantly different torsional loads were recorded whilst preparing various root canal types (mb, db and p). However, there was a significant positive correlation ($r = 0.48$, $P < 0.001$) between preoperative canal volumes, as calculated from μCT data, with higher torque scores generated in the 'constricted' root canals. Likewise, significant differences for four out of five file types were recorded when 'constricted' and 'wide' canals were compared ($P < 0.001$, Fig. 4).

Forces

Maximum apically directed forces ranged between 0.8 and 16.8 N, with the lowest and highest mean scores generated with S2 and F3 instruments, respectively.

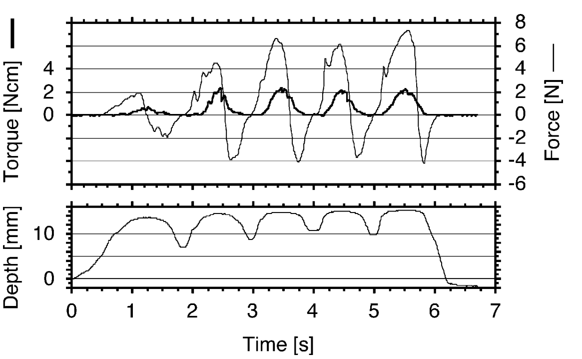

Figure 3 Typical data registration whilst preparing the palatal canal of a maxillary molar using a ProTaper finishing file 3. Note decreasing time lag between force and torque peaks. Torque denoted by solid line, force by fine line.

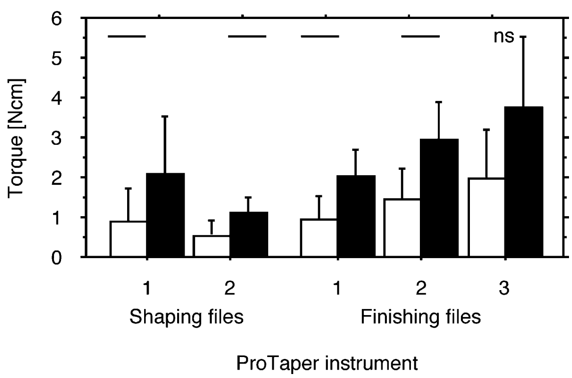

Figure 4 Torsional loads of ProTaper instruments whilst rotating in 'wide' (open bars) and 'constricted' canals (filled bars). Significant differences ($P < 0.001$) denoted by horizontal bars; $n = 32$, for finishing file 3; $n = 10$.

Table 1 Mean ± SD torque scores, grouped for the five ProTaper rotary instruments shaping files 1 and 2, finishing files 1–3

	S1 ($n = 45$)	S2 ($n = 45$)	F1 ($n = 45$)	F2 ($n = 45$)	F3 ($n = 15$)
Torque (N cm)	1.4 ± 1.2	0.8 ± 0.5	1.5 ± 1.1	2.1 ± 1.1	2.2 ± 1.4
Range (N cm)	0.1–5.4	0.2–1.9	0.2–3.3	0.3–4.7	0.4–5.2
Different to[a]	S2, F2, F3	S1, F1, F2, F3	S2, F2, F3	S1, S2, F1	S1, S2, F1

[a]Overall significantly different (ANOVA) $P < 0.001$, posthoc (Scheffé) $P < 0.05$.

Table 2 Mean ± SD apically directed forces, grouped for five ProTaper rotary instruments shaping file 1 and 2, finishing files 1–3

	S1 ($n = 45$)	S2 ($n = 45$)	F1 ($n = 45$)	F2 ($n = 45$)	F3 ($n = 15$)
Force (N)[a]	5.8 ± 3.4	4.6 ± 2.6	5.3 ± 2.5	5.6 ± 2.3	6.2 ± 2.7
Range (N)	1.5–16.8	1.0–13.8	0.8–12.3	1.1–11.1	1.6–10.7

[a]No statistically significant differences between groups (ANOVA).

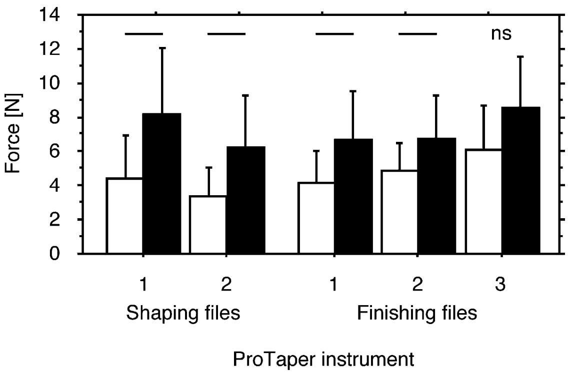

Figure 5 Apically directed forces in 'wide' (open bars) and 'constricted' canals (filled bars). Significant differences ($P < 0.001$) denoted by horizontal bars; $n = 32$, for finishing file 3; $n = 10$.

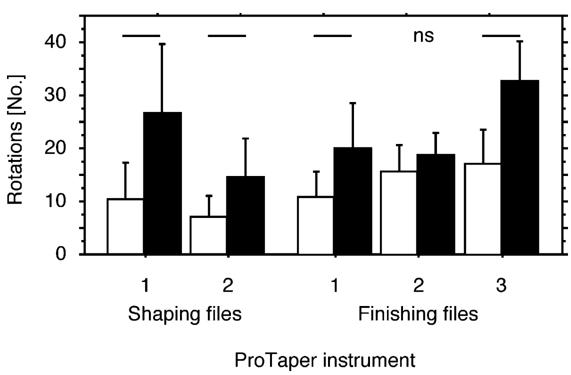

Figure 6 Numbers of rotations of ProTaper instruments in 'wide' (open bars) and 'constricted' canals (filled bars). Significant differences ($P < 0.05$) denoted by horizontal bars; $n = 32$, for finishing file 3; $n = 10$. Rotations counted when torque exceeded threshold of 0.01 N cm (see Materials and methods).

Table 3 Mean ± SD numbers of working rotations[a], grouped for five ProTaper rotary instruments shaping files 1 and 2, finishing files 1–3

	S1 ($n = 45$)	S2 ($n = 45$)	F1 ($n = 45$)	F2 ($n = 45$)	F3 ($n = 15$)
Rotations[b]	17.4 ± 13.0	10.9 ± 7.0	16.2 ± 8.5	17.0 ± 5.2	20.2 ± 10.1
Range	0.8–52.8	1.2–26.8	2.5–35.9	5.9–26.9	4.6–40.8

[a]Torque threshold 0.01 N cm.
[b]No statistically significant differences between groups (ANOVA).

Mean forces did not vary significantly between instruments (Table 2) and ranged between 5.3 and 6.2 N. Furthermore, there were no significant differences in apically directed forces when data were grouped for root types. However, there was a significant correlation between preoperative canal volume and apically directed force ($r = 0.48$, $P < 0.001$), with higher forces exerted in smaller root canals. Similarly, ANOVA confirmed significant differences between forces used in 'wide' and 'constricted' canals when data were grouped for instrument types ($P < 0.001$, Fig. 5).

Numbers of rotations

Finally, cutting rotations of the respective instruments were counted under the condition that torque exceeded a preset threshold. Interestingly, these scores varied considerably within each instrument type, in particular for shaping file 1 (Table 3). Overall mean numbers of rotations for various ProTaper instruments did not differ significantly (Table 3) and ranged between 10.9 and 20.2. Again, regression analysis revealed a significant correlation between preoperative canal volume and number of rotations ($r = 0.47$, $P < 0.001$). Likewise, preparation of 'constricted' and 'wide' canals resulted in significantly different numbers of rotations (Fig. 6).

Discussion

There is accumulating evidence suggesting that rotary NiTi instruments facilitate root canal preparation with minimal or no canal transportation (Peters *et al.* 2001, Ruddle 2002). However, instrument separation might occur more frequently with rotary systems than with conventional hand instruments and there remains a clinical concern even after in-depth introductory courses (Barbakow & Lutz 1997).

Consequently, physical parameters governing the fracture mechanisms of rotary endodontic instruments are of considerable interest. Sattapan *et al.* (2000a) outlined two distinct fracture mechanisms, i.e. torsional fracture and flexural fracture. Torsional fractures occur when the apical portion of a rotating instrument is forced into narrow root canals. Friction increases at this point, high torque is required to rotate the instrument and the fragile instrument tip is subjected to excessive torque (Blum *et al.* 1999b). This effect has been described as 'taper lock' since it might occur with similarly tapered instruments of varying tip diameters rather than with variably tapered instruments (Yared *et al.* 2002). Consequently, one of the design characteristics of ProTaper instruments is a variable taper along the cutting part of the instruments (Fig. 1).

Repeated bending in curved canals causes metal fatigue and subsequent instrument separation (Sattapan *et al.* 2000a). *In vitro* studies have indicated that rotary NiTi instruments have a predefined fatigue life and are able to withstand between 250 and 500 rotations in simulated metal canals with 90° curvatures and 5 mm radii (Haikel *et al.* 1999, Gambarini 2001, Peters & Barbakow 2002).

Operator-related factors and clinical ability are also important factors related to instrument separation (Yared *et al.* 2002) and consequently, electric motors and handpieces have been developed to simplify the use of NiTi rotary instruments. Although some of these handpieces are equipped with torque-limiting systems, operators will use varying apically directed force and speed of insertion. Furthermore, times required to prepare canals must differ greatly and, consequently, the risk of fatigue fracture will vary.

Whilst the problem of cyclic fatigue of NiTi instruments has been described in several studies under varying *in vitro* situations, little is known about the torque and force generated by these instruments during root canal preparation. Most of the latter studies are limited to the preparation of straight canals in anterior teeth and this is due to the construction of the respective torque transducers (Blum *et al.* 1999a,b, Sattapan *et al.* 2000b). However, a different approach to assessing torque and force generated by rotating ProFile .04 instruments in curved single-rooted teeth has been described recently (Peters & Barbakow 2002). This was achieved by incorporating a dynamic torque sensor into the rotational axis, with the result that torque is then measured between the motor and the shank of the endodontic instrument.

In the current study, ProTaper instruments were used to shape canals in extracted maxillary molars whose internal morphology had previously been assessed using micro computed tomography (Peters *et al.* 2000). Overall, mean maximum peak torque scores were 2.2 N cm and this result was lower than the 2.82 and 2.5 N cm previously recorded for Quantec (Tycom Corp., Irvine, CA, USA) and for ProFile .04 instruments (Dentsply Maillefer), respectively (Sattapan *et al.* 2000b, Peters & Barbakow 2002).

The present study appears to be the first to prove that torque is correlated not only to apically exerted force, but also to preoperative canal volume. Hence, preparation of narrow and constricted canals could subject rotary instruments to higher torsional loads. At the same time, apically directed force increased similarly when narrow canals were prepared. In fact, apically directed forces in excess of 10 N were exerted on finishing files in some severely curved and narrow canals. However, this amount of force did not produce excessive torque and did not cause instruments to fracture. The reason why these instruments did not fracture was probably related to a patent glide path being present at all times. For that purpose, we recommend, as a guideline, to enlarge canals to at least a size 015 K-File prior to the use of ProTaper instruments at WL.

Moreover, four instruments separated in pilot experiments and it might be speculated that specific instruments have their individual optimum force and that the forces used in the present study were acceptable for some rotary instruments, but may have been excessive for the delicate, differently designed ProTaper shaping instruments.

In the current study, the numbers of rotations during simulated shaping of root canals were also counted in order to address cyclic fatigue. This parameter was correlated significantly to canal volume and behaved in this respect similarly to torque and applied force. However, wide ranges were recorded for all five instruments and in particular, for shaping file 1. In one case, more than 50 rotations were required to prepare a 'constricted' canal. Earlier experiments using the same testing device had indicated that tapered rotary instruments (GT 20/.08, Dentsply Maillefer), which have a cross-sectional dimension at D3 similar to a shaping file 1, fractured after 250 rotations when tested in a simulated canal with 90° curve and 0.5 mm radius. Consequently, it might be advisable to discard ProTaper shaping files after four to five constricted canals.

Sattapan *et al.* (2000a) speculated that fatigue fracture might play a major role in Quantec instruments, but others have reported that cyclic fatigue was a minor factor for ProFile instruments when used correctly and discarded regularly (Yared *et al.* 2001). Apparently, the instruments' cross-sectional geometry does play an important role in cyclic fatigue.

However, torsional and flexural fractures are not mutually exclusive categories and cyclic fatigue simulation using metal canals cannot closely resemble clinical conditions because only minimal friction occurs between the rotating instrument and the holding device. Cyclic fatigue might occur differently if instruments are subjected to apically directed force and rotate in curved canals. Clinically, supra-threshold torque does occur for a limited time period only (Peters & Barbakow 2002) and it might be more appropriate to calculate the product of torque and time (area under torque curve in Fig. 3) in order to assess the amount of stress the instruments have been subjected to.

Conclusions

ProTaper instruments generated lower torque scores than those described previously for rotary instruments with U-file design. There were significant positive correlations between canal geometry and physical parameters during shaping. Furthermore, high forces used in some cases of 'constricted' canals were insufficient to fracture ProTaper instruments when a patent glide path was present. However, fractures might still occur even when using torque-controlled handpieces because of cyclic fatigue or other, yet unknown, factors. Consequently, more research is required to determine the exact fracture mechanisms and to optimize instrumentation guidelines.

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