A Novel Platform for *In Vitro* Analysis of Torque, Forces, and Three-dimensional File Displacements During Root Canal Preparations: Application to ProTaper Rotary Files

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Abstract

We proposed a new testing setup and *in vitro* experimental procedure allowing the analysis of the forces, torque, and file displacements during the preparation of root canals using nickel-titanium rotary endodontic files. We applied it to the preparation of 20 fresh frozen cadaveric teeth using ProTaper files (Dentsply Maillefer, Ballaigues, Switzerland), according to a clinically used sequence. During the preparations, a clinical hand motion was performed by an endodontist, and we measured the applied torque around the file axis and also the involved three-dimensional forces and 3-dimensional file displacements. Such a biomechanical procedure is useful to better understand the working conditions of the files in terms of loads and displacements. It could be used to analyze the effects of various mechanical and geometric parameters on the files' behavior and to get data for modelling purposes. Finally, it could contribute to studies aiming to improve files design in order to reduce the risks of file fractures. *(J Endod 2009;35:568–572)*

Key Words

Biomechanics, forces, *in vitro* experimental model, ProTaper file, root canal preparation, three-dimensional displacements, torque

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Nickel-titanium rotary files are now commonly used in endodontic treatments and make the treatment of root canals with complex shapes and curvatures easier. Nevertheless, these instruments present risks of separation during preparation. Even if the main mechanisms involved in these fractures have been often described (1, 2), biomechanical studies are still needed to better understand the reasons of these fractures and to try to reduce or to avoid them. In particular, those analyzing the files' working conditions in terms of involved loads and displacements could be helpful in the assessment of the files' separation risks (by comparison between the involved loads and the strength of the file). Different experimental setup and protocols have been proposed to study the forces developed during a root canal preparation on extracted teeth or synthetic blocks (1–6). Nevertheless, in some of them (4, 6), the displacement or the torque imposed to the file were only along a fixed axis relative to the tooth, which was not able to reproduce completely the actual clinical hand motion. In others, an actual clinical hand motion was performed (1–3), but only the force and the torque according to the apical direction were analyzed. We are aware of no study including a free clinical hand motion and a multidirectional measurement of involved efforts (forces and torque) and file displacements; this seems important to us in an advanced analysis of the biomechanical behavior of the rotary endodontic files.

Hence, the aim of the present work was to propose a new experimental setup and a protocol allowing such multidirectional analyses. We applied this procedure to study ProTaper files (Dentsply Maillefer, Ballaigues, Switzerland) during the preparation of fresh-frozen extracted cadaveric teeth. The values of forces are presented in three orthogonal directions, and the torque was measured around the file axis, the orientation of which changed during the preparations. Data variations according to the succession of the files in the operative sequence were analyzed. The concomitant 3D linear and angular displacements of the files were also calculated.

These kind of data should allow, for a given kind of instrument, one to better analyze the hand motion of an operator and possibly to compare different operators. They also could allow one to better quantify the loads applied on an instrument in order to possibly improve its design and, finally, to compare different kinds of files.

Material and Methods

Experimental Procedure and Testing Setup

Twenty human fresh frozen cadaveric mandibular central or lateral incisors with a straight and narrow canal coming from four men and two women (88 ± 10 years) were involved. They were thawed at room temperature before usage.

After the opening of the access cavity, the working length (WL) was assessed with a K-type file just visible at the apical foramen. Then, an initial manual preparation with K-type files was performed (up to WL from #8 to #15 and up to light resistance from #20 to #25). One of these manual files was then inserted in the canal, and the apical part of the tooth was embedded in a dental resin support (Lang Dental, Wheeling, IL), with the axis of the handle of the file in a vertical position to define the vertical axis of the sample. Two perpendicular radiographs were then performed doing a 90° rotation around the vertical axis. They were used in a custom-made software to determine the orientation of the apex.

The embedded tooth was then fixed on a specifically designed platform (Fig. 1) for root canal preparation with rotary files, with the apex oriented toward the operator. Teeth were then prepared using ProTaper Universal rotary files (Dentsply Maillefer) fixed into a handpiece (contra-angle with a 16:1 reduction ratio), powered by a micromotor set at a rotational speed of 320 revolutions per minute (X-SMART, Dentsply Maillefer).

The files were used according to the following sequence and preparation steps: shaping file 1 then 2 to WL minus 2 mm (S1WL-2 then S2WL-2), shaping file X (SX), shaping files 1 then 2 to WL (S1WL then S2WL), finishing file 1 then 2 to WL (F1WL then F2WL), and finishing file 3 to WL minus 1 mm (F3WL-1). A new set of files was used for each tooth.

All canals were prepared by the same right-handed well-trained endodontist (MO) who performed a clinical procedure (according to manufacturer guidelines), without any limitation or guidance of the movements of the handpiece and the files (freehand motion).Below the piece that held the tooth, we inserted a piezoelectric three-component load cell (9251A; Kistler, Winterthur, Switzerland) measuring the forces that the endodontist applied during the preparation of the root canal. The measurement errors were lower than 0.1 N in all three directions. Throughout the preparation we measured, according to the XYZ referential system (Fig. 1), the three components of the applied load: the force Fz along the vertical z-axis (directed from coronal part to the apex) and the parietal forces Fx and Fy along the x-axis and the y-axis (respectively directed from right to left and from posterior to anterior).

We measured the applied torque along the moving axis of the file because the orientation of the file axis varied during the preparation because of the freehand motion of the operator. For that, we developed a custom method using electrical measurements at the micromotor (current and voltage). A calibration procedure was performed using a weight-pulley system to apply well-known torques. It took into account the friction in the micromotor and concluded to a maximal error of 0.4 Nmm. All the loads and torque data acquisitions were computer driven by a program developed in Labview (National Instruments, Austin, TX).

We simultaneously analyzed the linear and angular displacements of the files during the preparation using a three-dimensional electromagnetic device (Fastrak; Polhemus, Colchester, VT). This device, commonly used for motion measurements in biomechanics, allows the tracking of the position of sensors relative to a referential frame linked to an electromagnetic field emitting box (transmitter). The accuracy of this device in our testing environment was assessed to 0.6 mm and 1°. During our tests, a sensor was fixed on the handpiece via a rigid plastic support (Fig. 1), and the transmitter was fixed on a wooden support. The position of the sensor was continuously measured during the preparations, and preliminary measurements gave us the position of the file relative to the sensor fixed on the handpiece. We then used these data and a rigid body assumption for the handpiece and the plastic support to calculate the actual 3D displacements of the file in the same referential system as for load measurements. We calculated the three linear displacements of one point (M) of the file (placed just at the insertion of the file in the handpiece) and the angles between the z-axis (vertical) and the axis of the rigid part of the file, directed from M to the tip, in the zx plane (alpha) and the yz plane (beta).

Data Analysis and Statistics

For each tooth and for each step of the preparation sequence, we obtained graphs representing the three components of forces and the torque developed by the operator throughout the preparation. From these curves, we determined the mean value, the positive and negative peaks of each force component, the mean value, and the positive peak of torque (the torque being always positive).

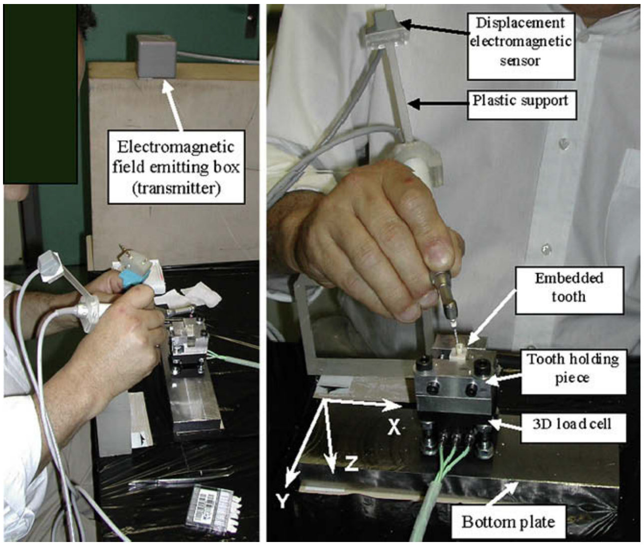

Figure 1. A global view of the testing platform; the bottom plate, the load cell, the tooth holding piece, and the embedded tooth are linked together and fixed on a table in front of the operator. A freehand motion is then applied by the operator, and the involved torque, forces, and three-dimensional file displacements are simultaneously recorded. (All data are expressed in the XYZ coordinate system.)

Two different statistical analyses were performed. First, paired Student *t* tests were performed to compare, at each step and for each force component, the magnitudes of the positive and the negative peaks and also to check if the mean value significantly differed from zero. Then, for each peak (positive or negative) and mean value, a one-way analysis of variance (ANOVA) with repeated measures was performed followed by a Scheffé post hoc test for multiple comparisons between the different preparation steps. The significance level was set at $p < 0.05$ for all the analyses.

Results

Global Curves for Torque, Forces, and Displacements

For each tooth and for each step of the preparation sequence, different graphs showing the fluctuations of forces and torque and those of file linear and angular displacements from the insertion to the withdraw of the file were obtained. An illustration of these data is presented for one tooth prepared with an S1 file at WL (Fig. 2*A* for forces and torque and 2*B* for file displacements).

Peak and Mean Values of Torque and Force Components

At each preparation step, the average and the standard deviation were then calculated all over the tested teeth for the peak and mean values of the torque and each force component (Fig. 3). The peak torque varied from 22.1 Nmm (F1WL) to 29.6 Nmm (S1WL). The negative peak of Fz was between 3.2 N (S1WL) and 5.0 N (F3WL-1); the positive Fz peak was between 3.2 N (SX) and 7.1 N (F1WL). The negative peak of Fx ranged from 3.1 N (F3WL-1) to 4.8 N (S2WL) and the positive one from 0.6 N (F3WL-1) to 2 N (S2WL). The negative peak of Fy ranged from 6.3 N (F3WL-1) to 8.8 N (S2WL) and the positive one from 1.8 N (F3WL-1) to 3.7 N (S2WL).

The following analyses were then performed:

1. Comparisons between the different preparation steps: peak and mean forces and torque varied significantly between the different

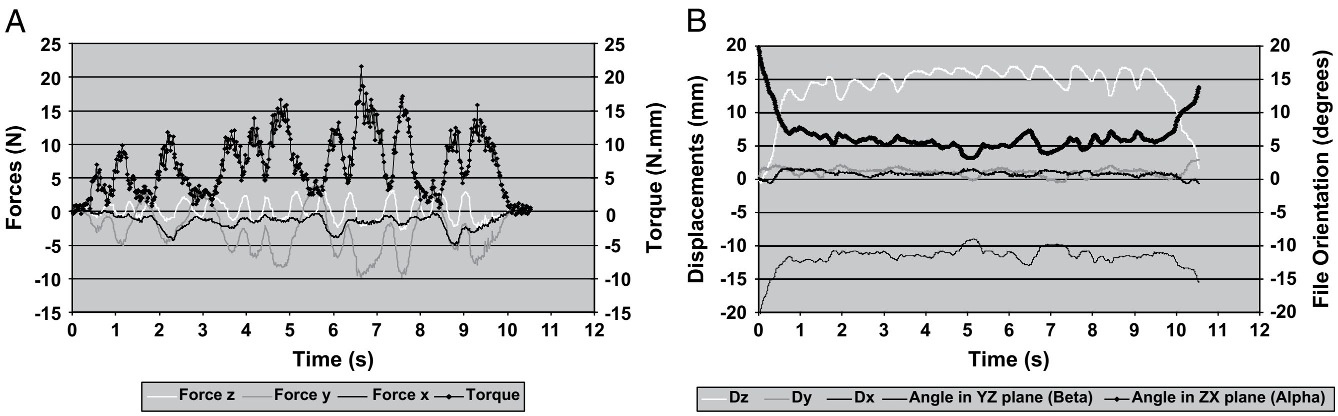

Figure 2. Examples of loads and displacements curves showing simultaneously the three force components and the torque (*A*) and the three-dimensional displacements (*B*) during the preparation of one of the tested teeth with the first shaping file at WL (S1WL).

steps of the preparation sequence (ANOVA p values for torque and each force component in Fig. 3). The results of post hoc multiple comparisons between the eight different steps are presented below the histograms in Figure 3.

2. Analysis of loads at a given preparation step: at a given preparation step, the magnitude of the positive peak was significantly higher than the negative one for Fz (except for SX and F3WL-1), indicating that the apical forces were higher than the coronal ones; the negative peaks were significantly higher than the positive ones for Fx and Fy at all steps of the sequence showing that the parietal forces were higher in the right side than in his left side and higher in the posterior direction than in the anterior direction. The mean values of forces and torque during the preparation were significantly different from zero except for Fz at 3 steps (S2WL-2, SX, and F3WL-1).

Discussion

Today, there still remains a need for investigations to better understand and try to avoid the separation of rotary nickel-titanium files during root canal preparation. Some authors performed static and fatigue tests on files (7–13); others analyzed the involved apical force and file torque during the preparation of synthetic blocks or extracted teeth (1–6). These last studies analyzing the files working conditions in terms of involved loads could be helpful in the assessment of the files' separation risks by comparison between the involved loads and the failure loads of the file (the ratio between the applied load and the failure load has been defined as the safety quotient by some authors [2]). In some of them (4, 6), the displacement or the torque imposed to the file were only along a fixed axis relative to the tooth, which was not able to reproduce completely the actual clinical hand motion but could present the advantage to be free from operator bias when the procedure is fully engine driven. In other studies, a freehand motion was performed (1–3), leading to a three-dimensional motion of the file. Their advantage was to simulate the actual clinical situation, but their results were operator dependent. We chose this last working way because our aim was to test the files in conditions as close as possible to the clinical ones and because the ProTaper system is advocated to be used with a brushing and outstroke motion, which is a complex three-dimensional hand motion.

To our knowledge, our experimental setup is the first one allowing a clinician to reproduce a three-dimensional clinical hand motion and to perform a multidirectional analysis of forces, torque, and rotary endodontic file displacement during a root canal preparation. In the previous studies, the force, the torque, and the file displacement were only analyzed according to a fixed direction (usually the apical one). Compared with other studies, our setup provides force data in the apical-coronal direction but also forces in anteroposterior and mediolateral directions. Moreover, we measured the torque around the axis of the rigid part of the file (which was mobile during operation); in the previous studies in which a clinical hand motion was performed, the applied torque was measured in a fixed direction using a transducer fixed between the tooth holder and the testing frame, which could lead one to miss a part of the actual torque when the axis of the file deviated from the one of the transducers. To measure the applied torque along the moving axis of the file, we developed an electrical measurement setup at the micromotor. This needs a calibration procedure that should be repeated at the beginning of each new testing session to take into account the wear in the micromotor or when a new micromotor is used.

Another originality of our protocol is the three-dimensional analysis of the linear and angular displacements of the files during preparation. This is interesting when analyzing the hand motion of a given operator and also for a better understanding of the working way of the files by a combined analysis of forces and displacements.

The obtained graphs allowed us to simultaneously analyze the fluctuations of forces, torque, and file displacement while preparing the canal (Fig. 2*A* and *B*) and can give useful qualitative information on any particular phenomenon occurring during the operation such as a screwing. Moreover, they showed that file angulations differed from zero during preparation (Fig. 2*B*), confirming the importance of measuring the torque along the file axis.

The mean and peak values of loads gave quantitative data on the hand motion performed by the operator and allowed comparisons between the different steps of the sequence. Regarding the hand motion, the forces were higher in the apical direction than in the coronal direction, higher in the right side than in his left side (an explanation can be that the operator was right-handed), and higher in the posterior direction than in the anterior direction. Peak forces and torque varied significantly between the different steps of the preparation sequence, and our study underlined some post hoc contrasts between the different steps for each studied mechanical parameters. In particular, for the apical force, the highest peaks were observed with the last shaping file (S2WL) and the two first finishing files (F1WL and F2WL), indicating that they mainly work during apical progression. Despite the differences

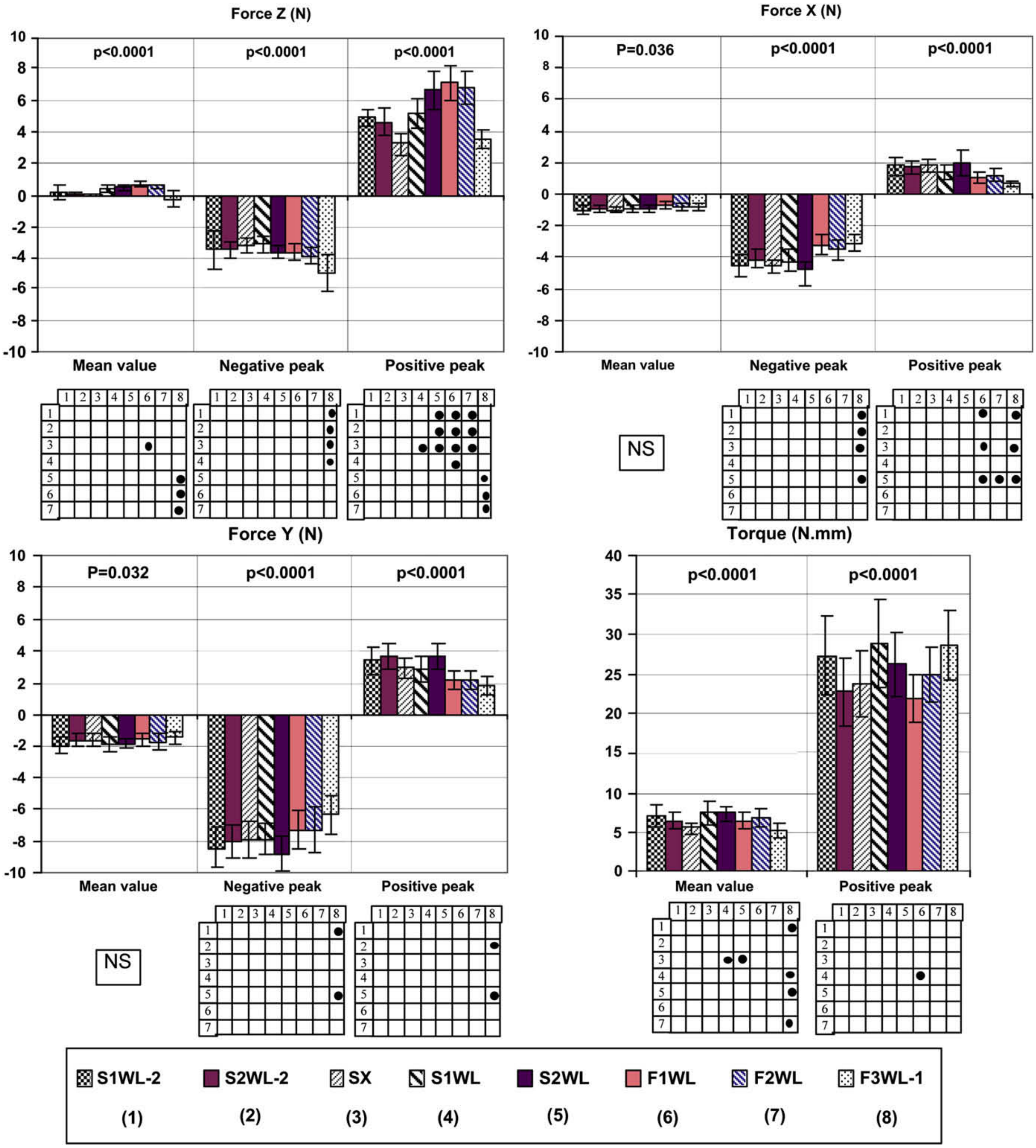

Figure 3. The mean and peak values of each force component and torque for the different files and preparation steps (mean and standard deviation for the 20 tested teeth). The ANOVA p values are presented on the histograms, and the results of the subsequent post-hoc multiple comparisons between the different preparation steps (from 1 to 8) are also presented below the histograms (dark dots correspond to significant differences at a 0.05 level and NS means that no significant difference was found in the multiple comparisons for a given parameter).

in teeth preparation and measurement procedures, the magnitudes of our apical forces and torques were in agreement with some previous data in the literature (4).

In summary, we presented a new testing setup that should allow, for a given kind of instrument, one to better analyze the hand motion of an operator and possibly to compare different operators. It also could allow, in operative situations close to clinical ones, one to better quantify the applied torque and forces on an instrument in order to possibly improve its design and, finally, to compare different kinds of files. The effect of parameters such as the geometry of the canal could also be analyzed, and the protocol could also be applied to test the synthetic blocks. The obtained data could finally be used in the implementation and validation of finite elements models of endodontic files and root canals (14–16) that could provide complementary information about contact areas between file and canal or about stresses of the file and such studies are currently in progress.

Acknowledgments

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