Prediction of thrust force and torque in canal preparation process using Taguchi method and Artificial Neural Network

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Abstract
Root canal preparation is a vital procedure during the treatment of pulposis and periapical periodontitis. However, the improper control of thrust force and torque in root canal preparation will cause nerve damage and cell necrosis. The aim of this study was to investigate and optimize the main factors influencing thrust force and torque and to establish an efficient predictive model for root canal preparation. This study was conducted on fresh bovine bones due to the similarity of structure and density with human teeth. A novel experimental platform was first built to measure the force and torque in canal preparation of different parameters. The effect of the experimental results on thrust force and torque was investigated based on Analysis of variance (ANOVA). The results indicated that the diameter of instrument, width of root canal, and feed rate are the most significant factors influencing the thrust forces and torque ($p < 0.05$). Based on the above experiments, a Radial Basis Function Neural Network (RBFN) model was established to predict the thrust force and torque in a wider range of parameters. In confirmation tests, RBFN showed an excellent predictive model for prediction of thrust force and torque (error less than 14%) in canal preparation.

Keywords
Thrust force, torque, radial basis function neural network, Taguchi method, root canal preparation

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Introduction
Root canal preparation is one of the indispensable steps in the treatment of pulposis and periapical periodontitis.¹ The aim of the canal preparation is to clean the root canal system efficiently and to maintain the original root canal anatomy by means of nickel titanium files.²,³

In the clinical preparation process, most of root canals are curved, which may lead to the excessive force and torque distribution in the contact area between root canal and instruments. The improper force and torque may cause frequent instrument breakage and adverse histological effects, which will result in dentin perforation and considerable damage to surrounding tissue.⁴,⁵ Therefore, it is vital to understand and clarify critically factors influencing canal preparation process...
and develop effective relationships for the effects of preparative conditions with instrumental and root canal geometry on the thrust force and torque to improve instrumental designs and to instruct clinician in operations.

Many researches were carried out to investigate the influencing factors of the thrust force and torque during canal preparation. Yum et al.\(^8\) pointed out that the size of nickel titanium files is a key element affecting the force and torque during the canal preparation. Based on finite element analysis (FEA), Kim et al.\(^7\) investigated the effect of different size and cross-sectional area on the stress of Ni-Ti file in the preparation process and reached the same conclusion as Blum et al.\(^8\) studied on the influencing factors of thrust force and torque. It was seen that increasing diameter of Ni-Ti file results in the larger force and torque. Lertchirakarn et al.\(^9\) investigated the influential weight of different factors (dentine thickness, cross-sectional area, and root canal curvature) on force and torque based on FEA during canal preparation process. They found that the curvature of root canal is the most important factor affecting stress concentration. Lopes et al.\(^10\) found that the different curvatures of root canal would cause stress concentration on the dentin. Tokita et al.\(^11\) studied the variation of force and torque induced in the canal preparation process under different experimental parameters. The results showed that the feed motion would quite affect the generated force and torque. However, these models are valid within the experimental ranges of parameters only while the structure of human tooth and the surgical conditions are complex clinically. Most researches were not satisfied with the conclusion drawn by experimental data itself, while few studies have been conducted to develop effective model to predict thrust force and torque considering structure of root canal and Ni-Ti file and surgical conditions.

Artificial Neural Network (ANN), a novel data processing technique, provided a new method for the prediction and optimization of force and torque in a wider range of fields such as endodontist and machining process.\(^12,13\) In this study, we explore and optimize experimentally the canal preparation process by Taguchi method,\(^14\) analysis of variance (ANOVA),\(^15,16\) and Artificial Neural Network (ANN)\(^17\) to enable prediction of thrust force and torque as relationships of nickel-titanium geometry and preparative conditions. Firstly, an experimental platform for the force and torque measurement induced by nickel titanium files during canal preparation was established. A microcomputer numerical control (CNC) was used to control the feed motion during experiments and a custom-made clamp was applied to fix the self-defined root canals. Next, considering the structure of Ni-Ti file and root canal, the influence of different factors on thrust force and torque was investigated based on Taguchi and ANOVA. Furthermore, prediction of thrust force and torque was realized with respect to preparative parameters (diameter of nickel titanium file, width and curvature of root canal, and feed rate) based on a well-trained radial basis function neural (RBFN) network, which was used to examine the responses in a wider range.

**Basic of root canal preparation**

An adult tooth is generally composed of crown, enamel, dentin, pulp, root, et al. Pulp disease is a common disease in stomatology nowadays. It comprises inflammation of the pulp and periapical periodontitis. The clinical treatment of choice for management requires the elimination of microorganisms and their products from the root canal system,\(^8\) as shown in Figure 1(a). In order to unify the experimental variables and to reduce the statistical error, a parametric model of root canal was built including the width denoted as \(d\), length denoted as \(L\), and curvature of root canal denoted as \(\alpha\), shown in Figure 1(b).

Ni-Ti (nickel-titanium) file was the most commonly used instrument in the root canal preparation process clinically.\(^18\) The geometric structure of Ni-Ti files consists of three parts: the filling part, the neck part, and the tail part (as shown in Figure 1(c)). The tail part is connected to the canal motor and transfers momentum to the filling part; the neck part connects the filling and tail part; the filling part is the most important part and usually consists of four filling edges. In the filling process, the four edges are simultaneously involved in filling the lateral wall of canals. As the operation progresses, the length of cutting edges gradually increases and the chip discharges along the cutting edges.

The root canal preparation was to remove the infected pulp by using Ni-Ti files, as we called filling process. The filling process is complicated, in which the force and torque are influenced by many factors, such as angle of canals. In order to analyze the filling process in detail, a dimensional model is presented in Figure 1(d) and (e). The filling process was mainly influenced by the type of Ni-Ti file and root canal system, including spindling speed spindling speed \(v\), see Figure 1(d) and (e)), feed rate \(f\) (see Figure 1(d)), diameter of Ni-Ti file \(D\) (see Figure 1(c)), helical angle \(\beta\) (see Figure 1(c)), width and curvature of canal \((d\) and \(\alpha\) (see Figure 1(b)), rake angle \(\gamma\) (see Figure 1(c)), et al. As shown in Table 1, the above factors were analyzed by other researches and we found the conclusion that feed rate \(f\), diameter of Ni-Ti file \(D\), width and curvature of canal \((d\) and \(\alpha)\) are four factors that have a significant impact on the thrust force and torque during canal preparation.
Figure 1. (a) View of root canal preparation process. (b) Structure of root canal. (c) Structure of nickel-titanium file. (d and e) Schematic illustration of the preparation process.

Table 1. Recent researches about influencing factors in preparation process.

| Factors              | Variation ranges | Criteria weight | References                                      |
|----------------------|------------------|-----------------|------------------------------------------------|
| Spindling speed      | 200–500 rpm      | LI              | Lee et al.\(^1\) pointed out that increasing tool rotational speed resulted in significant influence when speeds ranged from 500 to 3000 rpm. |
| Feed rate            | 15–25 mm/min     | AI              | Geometrically, the root canal is cut by the contact between the Ni-Ti file and root canal. The forces and torque will be induced during the process of removing the bone, which can be determined by difference of the diameter of Ni-Ti file and the width of canal. |
| Diameter of Ni-Ti file | 0.35–0.50 mm   | AI              | Rajamurugan et al.\(^2\) pointed out that the helical angle has slight influence on the thrust force. |
| Width of canal       | 0.25–0.35 mm     | AI              | Sadeghi and Poryousef\(^3\) reported that the curvature of root canal is an important factor influencing the stress generated in preparation process and for the success in endodontic treatment. |
| Helical angle        | 30°–45°          | I               | The rake angle of Ni-Ti files is generally set as 25° with 5° deviation, which is viewed as a constant parameter in our study. |
| Curvature of canal   | 30°–50°          | AI              |                                                 |
| Rake angle           | 25°              | I               |                                                 |

AI: absolutely important; I: important; LI: little important.
In the clinical canal preparation, cutting force is induced by a root canal motor and distributes into $x$-, $y$-, and $z$-axes. Specifically, excessive force along $z$-axis acts directly and will cause damage on the dental nerves which lay beneath the roots. Therefore, the force research in this study focuses on $z$-axis, which is defined as thrust force. Theoretically, the thrust force is a kind of load applied to the root canal. Wherein, as shown in Figure 1(a), the direction pointing to the bottom of root canal is defined as positive direction of $z$-axis, while the direction away from that is the negative direction of $z$-axis.

In addition, a preliminary test was conducted to explore the force and torque variation, as shown in Figure 2. In fact, the measured thrust force and torque are mixed with the noise signal which comes from the vibration of devices, such as CNC. Therefore, according to the previous research, a noise signal filtering method using MATLAB Simulation was applied in the experiments to eliminate the influence of noise, the results of preliminary experiments after filtering process are shown in Figure 2(b) and (d).

Specifically, the thrust force variation after filtering process with the structure of root canal is shown in Figure 2(b). In order to illustrate the thrust force clearly, two segments (straight and curved part) of root canal are divided by point $P_a$, $P_b$, and $P_c$. During the
interaction between NiTi file and root canal, the force obtained in the preliminary experiment is composed by two types of cutting force: screw-in force and intrude force. Wherein, the screw-in force generates due to the cutting interaction between cutting edge and root canal walls, which acts on the negative direction of z-axis. Besides, the intrude force is induced because of the pressure imposed by dentists and NiTi file’s own extrusion effect, which acts on the root canal along z-axis positively. Moreover, during the straight canal preparation (from Pa to Pb), the screw-in force plays the majority role on the force generation, which results in the force increasement along the z-axis until the maximum force $F_1$. And then, with the ongoing movement of NiTi file along curved canal, from Pb to Pc, the length of NiTi files’ cutting edge involved in cutting process increased gradually, which leads to the increasing of intrude force on the root canal. From the Figure 2(b), the intrude force plays the larger role on the force generation, which results in the force growth along the positive direction until the maximum force $F_2$. In the meanwhile, the peak-to-valley values of torque almost remain steady, hence, the maximum value is selected as the research object in this study.

**Design of experiments**

An experimental platform was established to conduct the canal preparation experiments in vitro. Due to the complicated structure of the human tooth, it’s difficult to get the teeth with the unified structure during clinical experiments. Meanwhile, considering the similarity of biomechanical properties between bovine bones and teeth, the material adopted in this study was fresh bovine bone (age 3–4 years) of foreleg which was acquired from a butcher 3 h after the beef was butchered. As shown in Figure 3, a new specimen processing method of experimental bovine bones was proposed and it can provide ideas for the variable control in experiments and for the replacement of resin canals that commonly used in dental researches. In order to guarantee reproducible results, the in vitro tests were repeated three times for each test condition.

- In step 1, a complete fresh beef foreleg bone was processed into 50–80 mm wide blocks by milling tools. In this step, the marrow and meat were scraped so that the cortical part was remained only to approach the performance and parameters of the root canals of human teeth as much as possible.
- In step 2, the bone blocks were processed into $25 \times 20 \times 5$ mm size samples by milling, grinding, and polishing.
- In step 3, the samples were milled to generate the shape of the root canal by the G-code controlled by a three-axis computer numerical control milling machine (CNC4030-800W, Jing Yan, China). In this step, the straight canal was processed into a 10 mm size. Meanwhile, the width and curvature (d and $\alpha$) of the root canal with various parameters could be obtained.

In this paper, the experimental platform for the filling process was first built. The platform has three components A, B, and C, as shown in Figure 4.

- Part A: machining system. In part A, the experimental specimens were fixed on the precision bench clamp. A nickel-titanium file driven by an Endodontic Micromotor was fixed on the CNC machine as shown in Figure 5(a). During the experiments, the specimen machined with canals
was fitted with a planar specimen during the filling experiments as shown in Figure 5(b). Due to the existence of the preset canals, the fitting of two specimens plays a role of guiding and will not be machined in the filling process.

- **Part B:** CNC system. In part B, a computer numerical control milling machine (CNC4030-800W, Jing Yan, China) connected to the Endodontic Micromotor was used for controlling the tool path and feed rate during experiments.
- **Part C:** measuring system. In part C, a precise dynamometer (9119AA2, Kistler, Switzerland) was to measure the values of thrust force and torque during experiments. The charge amplifiers (5080A100, Kistler, Switzerland) were used to transfer signals of thrust force and torque to a laptop (ThinkPad, Lenovo, China), which was used for data handling and analysis.

In this study, diameter of instruments, width of root canals, feed rate, and curvature of root canals were set as the influencing factors to predict thrust force and torque. The experiments are planned and carried out using the Taguchi experimental design of orthogonal arrays. The parameters with levels are shown in Table 2. The orthogonal experiments were selected on account of its ability to confirm the interaction between different experimental factors. The $L_{27}^1$ orthogonal array is shown in Table 3 and the four factors are respectively distributed in lines 1, 2, 5, and 9.

### Results and discussion

The experimental results of 27 groups including $F_1$, $F_2$, and $M$ were shown in Table 4. The filling experiments were conducted under dry condition and the filling situation was evaluated by the thrust force and torque caused by nickel-titanium files. Each filling experiment was repeated two times. The evaluation and analysis of experimental data were conducted on Minitab after the error data was eliminated. The experimental results will be discussed in 4.1 and 4.2.
Clinically, the canal preparation is influenced by different kinds of factors, for example, structure of root canal, types of NiTi files, and operation of dentists. In this paper, four parameters are selected according to preliminary experiments and other researches, as shown in Table 2. Wherein, the width and curvature of root canals are decided by patients, as defined as the origin factors, while diameter of NiTi files and feed rate are controlled by dentists, as defined as controllable factors. Therefore, it means that the dentists have to correctly deal with the various combinations between the origin factors and controllable factors to ensure the successful rate of canal preparation.

**Analysis of the S/N ratio**

In order to estimate the influence of different factors on the thrust force during the root canal preparation, the signal-to-noise ratios (S/N) for each factor are calculated. The signals are indicators of the effect on the responses and the noises are measures of the influence on the deviations from the average responses, which accounts for the sensitiveness of the experiment output to the noise factors. In this study, the S/N ratio was chosen according to the criterion the-smaller-the-better in order to minimize the response. The S/N ratio model of the-smaller-the-better can be expressed in equation (1).

\[
\frac{S}{N} = -10 \log_{10} \frac{1}{n} \sum_{i=1}^{n} y_i^2
\]  (1)

where \( n \) is the number of repetitions of the experiment and \( y_i \) is the average measured value of experimental data \( i \).
The results of S/N are shown in Figure 6(a) and (b), which can be indicated that the thrust force has increased with the increase of diameter of Ni-Ti files and feed rate. An increase in the file diameter and feed rate increased the cross-sectional area of unmoved chip, which led to an increase force on the dentin. The increase of width of root canals has lead to a decrease in thrust force. Nevertheless, the increase of curvature of root canal has a positive impact on thrust force 1 and a negative impact on thrust force 2. The increase in the curvature of the root canal will result in a dramatic change in the thrust force, which reaches the same conclusion as other researches. At the same time, as we can see from Figure 6(c), the increase of diameter and feed rate have led to an increase of torque. But, with the increase of width of root canal, the torque has decreased. On the contrary, the torque has decreased with the increase of curvature until $40^\circ$. Then, it has increased. The most effective factor is the diameter of Ni-Ti files which influence the thrust force1 and torque, and followed by width of root canal, feed rate, and curvature of root canal. However, on the thrust force 2, the most influential factor is feed rate, and followed by diameter of Ni-Ti files and width of root canal. The least factor is the curvature of root canal.

### Analysis of variance (ANOVA)

#### Analysis of thrust force

Analysis of variance (ANOVA) was conducted to obtain the relationship between $F_1$ with experimental factors. The method for structure analysis of ANOVA can be shown in equations (2) and (3).

$$X_{ijk} = \mu_{ij} + \epsilon_{ijk}$$  \hspace{1cm} (2)

$$\epsilon_{ijk} \sim N(0, \sigma^2)$$  \hspace{1cm} (3)

where $X_{ijk}$ is the experimental results, $\mu_{ij}$ is the mean value, $\sigma^2$ is the variance, $i, j, k$ are the levels of factors.

In the ANOVA, $p$-value is a convince and efficient method to analysis the experimental results of parameter design and is applied as the standard of factors elimination technique. Specifically, $p$-value $> 0.05$ means that the single factor/interactive factor has no or minimum influence on the results. As shown in Table 5, the diameter of instrument, width of canal, and feed rate are significant factors influencing the $F_1$ with the $p$-value less than 5% for the 95% confidence interval. The curvature of root canal is not a significant factor, whereas, the interaction of factors: diameter of instrument and width of canal have a significant impact over

### Table 4. The factors and results of L27 experiments.

| No. | Factor | Conditions | $F_1$ (N) | $F_2$ (N) | $M$ (N mm) |
|-----|--------|------------|----------|----------|------------|
| A   | B      | C          | D        |          |            |
| 1   | 0.35   | 0.20       | 15       | 30       | -2.45      | 3.14       | 0.50 |
| 2   | 0.35   | 0.20       | 20       | 40       | -3.76      | 4.14       | 0.50 |
| 3   | 0.35   | 0.25       | 20       | 50       | -4.19      | 4.86       | 0.68 |
| 4   | 0.35   | 0.25       | 15       | 40       | -1.76      | 2.30       | 0.41 |
| 5   | 0.35   | 0.25       | 20       | 50       | -3.25      | 3.32       | 0.61 |
| 6   | 0.35   | 0.25       | 25       | 30       | -3.98      | 3.62       | 0.58 |
| 7   | 0.35   | 0.30       | 15       | 50       | -1.22      | 1.64       | 0.33 |
| 8   | 0.35   | 0.30       | 20       | 30       | -1.96      | 3.15       | 0.42 |
| 9   | 0.35   | 0.30       | 25       | 30       | -3.35      | 2.86       | 0.54 |
| 10  | 0.40   | 0.20       | 15       | 40       | -2.97      | 4.72       | 0.62 |
| 11  | 0.40   | 0.20       | 20       | 50       | -4.32      | 5.58       | 0.76 |
| 12  | 0.40   | 0.20       | 25       | 30       | -5.28      | 6.08       | 0.96 |
| 13  | 0.40   | 0.25       | 15       | 50       | -2.03      | 4.98       | 0.54 |
| 14  | 0.40   | 0.25       | 20       | 30       | -3.72      | 6.51       | 0.60 |
| 15  | 0.40   | 0.25       | 25       | 40       | -4.92      | 8.24       | 0.72 |
| 16  | 0.40   | 0.30       | 15       | 30       | -1.19      | 3.94       | 0.55 |
| 17  | 0.40   | 0.30       | 20       | 40       | -2.82      | 5.52       | 0.60 |
| 18  | 0.40   | 0.30       | 25       | 50       | -4.19      | 4.85       | 0.65 |
| 19  | 0.50   | 0.20       | 15       | 50       | -3.26      | 11.12      | 0.65 |
| 20  | 0.50   | 0.20       | 20       | 30       | -4.35      | 11.84      | 0.88 |
| 21  | 0.50   | 0.20       | 25       | 40       | -6.16      | 8.96       | 1.08 |
| 22  | 0.50   | 0.25       | 15       | 30       | -2.54      | 7.28       | 0.72 |
| 23  | 0.50   | 0.25       | 20       | 40       | -4.02      | 10.12      | 0.78 |
| 24  | 0.50   | 0.25       | 25       | 50       | -5.71      | 10.38      | 0.96 |
| 25  | 0.50   | 0.30       | 15       | 40       | -1.80      | 5.81       | 0.64 |
| 26  | 0.50   | 0.30       | 20       | 50       | -3.35      | 6.78       | 0.68 |
| 27  | 0.50   | 0.30       | 25       | 30       | -4.93      | 7.72       | 0.80 |
the $F_1$; and the interaction of factors: diameter of instruments and feed rate do not significantly impact over the $F_1$.

Meanwhile, Table 4 represents the ANOVA for the $F_2$ in the filling process, which shows that the diameter of instrument, width of root canal, and feed rate are significant factors influencing $F_2$ ($p$-values < 0.05). The interaction of factors: diameter of instrument and width of root canal has significant impact over $F_2$; Although minimal but the insignificant effect of width of root

![Figure 6. Effect of filling parameters on thrust force and torque; (a) thrust force 1, (b) thrust force 2, and (c) torque.](image)

**Table 5.** The results of ANOVA of thrust force and torque.

| Factor                             | Degree of freedom | Sum of squares | Mean square | $F$-value | $p$-Value |
|------------------------------------|-------------------|----------------|-------------|-----------|-----------|
| Thrust force 1                     |                   |                |             |           |           |
| Diameter of file                   | 2                 | 5.79           | 2.89        | 28.01     | 0.01      |
| Width of root canal                | 2                 | 8.00           | 4.00        | 38.70     | 0.01      |
| Diameter of file with feed rate    | 2                 | 0.14           | 0.14        | 1.31      | 0.02      |
| Feed rate                          | 2                 | 30.66          | 15.33       | 148.32    | 0.02      |
| Total                              | 8                 | 44.59          |             |           |           |
| Thrust force 2                     |                   |                |             |           |           |
| Diameter of file                   | 2                 | 145.29         | 72.65       | 50.28     | 0.01      |
| Width of root canal                | 2                 | 19.07          | 9.54        | 6.60      | 0.01      |
| Width of root canal with feed rate | 2                 | 1.64           | 1.64        | 1.13      | 0.03      |
| Feed rate                          | 2                 | 11.91          | 5.95        | 4.12      | 0.02      |
| Diameter of file with width of root canal | 2                 | 1.11           | 1.11        | 0.77      | 0.03      |
| Total                              | 10                | 179.02         |             |           |           |
| Torque                             |                   |                |             |           |           |
| Diameter of instrument             | 2                 | 0.38           | 0.19        | 56.12     | 0.01      |
| Width of root canal                | 2                 | 0.11           | 0.06        | 16.44     | 0.01      |
| Feed rate                          | 2                 | 0.23           | 0.11        | 33.145    | 0.01      |
| Width of root canal with feed rate | 2                 | 0.01           | 0.01        | 3.45      | 0.08      |
| Curvature of root canal            | 2                 | 0.02           | 0.02        | 0.19      | 0.08      |
| Total                              | 10                | 0.75           |             |           |           |
canal and curvature of root canal, feed rate and curvature of root canal are also present over $F_2$ of the filling process ($p$-values $> 0.05$).

The relationships between and diameters of instruments with different widths of root canals are shown in Figure 7. It can be observed that thrust force increased with the arising of feed rate, diameter of files, and curvature of root canal. Moreover, the increasing of feed rate, diameter of file, and the curvature of root canal caused the increasing of the thickness of cutting chip, that is known as “size effect,” which led to the increase in thrust force applied by the nickel-titanium file.

From Table 5, the ANOVA results represented that diameter of file has the greatest effect on thrust force 1, followed by width of root canal and feed rates. In addition, width of root canal was the most influential factor on thrust force 2 and followed by diameter of file and feed rate.

Peak force $F_1$ was induced during the preparation of straight canals, and $F_2$ was the peak force induced in the preparation process of curved canals. According to the S/N ratio and ANOVA, feed rate has the most significant influence on the thrust force during straight canal preparation. In clinical, dentist would better preferentially adopt lower feed rate to avoid adverse effects on dentin. Meanwhile, during the curved canal preparation process, lower diameter of Ni-Ti files was compatibly selected to reduce the probability of surgical failure. In fact, the structure of root canals is complex, which were combined of a series of straight and curved canals. Hence, in order to ensure the quality of surgeries and to improve the efficiency, a small size of

Figure 7. Interactions between thrust force and diameter of instruments with different widths of root canals: $d$ is the width of root canal: (a) feed rate = 15 mm/min, $F_1$, (b) feed rate = 20 mm/min, $F_1$, (c) feed rate = 25 mm/min, $F_1$, (d) feed rate = 15 mm/min, $F_2$, (e) feed rate = 20 mm/min, $F_2$, (f) feed rate = 25 mm/min, $F_2$, (g) feed rate = 15 mm/min, $M$, (h) feed rate = 20 mm/min, $M$, and (i) feed rate = 25 mm/min, $M$. 

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Ni-Ti file and a higher feed rate are preferred to produce a smooth wall of root canal at the very beginning. Then, a larger size of Ni-Ti file and lower feed rate would be used to prepare the high curvature canal.

**Analysis of torque.** Table 5 presents that the diameter of instrument, width of root canal, and feed rate are significant factors influencing $M$ ($p$-values < 0.05), whereas the interaction of factors has no significant impact on the $M$ ($p$-values > 0.05).

In clinical, the excessive torque exerted on the files are prone to cause the fatigue and torsional fracture of Ni-Ti files, especially in the curved canal preparation process. In general, the torque value was set usually by a root canal motor. During canal preparation, the torque can be controlled by dentists. Research pointed out that the excessive torque is one of the main reasons of the NiTi file separation. Clinically, the manufacturers will provide an applicative range of torque of NiTi files during canal preparation. For example, around 1.5 N mm to the diameter 0.5 mm of NiTi files; 2 N mm to the diameter, 0.4 mm of NiTi files. According to the analysis of torque in Table 5, torque generation is influenced mainly by the diameter of instrument and feed rate. Specifically, it is necessary for dentists to apply the torque below the suggested values during the large diameter of instrument and feed rate to avoid the separation. In addition, a greater value beyond the recommended torque can be used in lower diameter of instrument and feed rate to improve the cleaning efficiency of root canal preparation.

Overall, in order to avoid the accidents, such as steps and separation, caused by improperly setting the parameters, according to the ANOVA, it can be indicated that, firstly, as for the mild origin factors, such as the 0.35 mm of width and 30 mm/m of curvature in root canal, it should be cooperated with the 0.5 mm diameter of NiTi files to improve the efficiency of canal preparation.

Secondly, as for the rigorous combinations within origin factors or controllable factors due to the variety anatomical structures of human teeth, such as 0.25 mm width of root canal with the 50 mm/m curvature of root canal. The improper selection of the diameter of root canal and feed rate will lead to the dramatical increase of thrust force and torque. In our study, according to the Table 5, it is suggested that the dentists should focus more on the primary factor which has the main influences on the results ($p$-value < 0.05), such as width of root canal on $F_1$ and diameter of file of $F_2$.

Thirdly, it can be noticed from Table 5 that there are the different selections of controllable factors according to the ANOVA of $F_1$ and $F_2$, such as the width of root canal ($F$-value = 38.70) and diameter of file ($F$-value = 50.28). Therefore, it is suggested the dentists should take into account the influence of $F_1$ when they are preparing the straight canals, as adjust the controllable factors during the preparation of curved canals.

**Estimation of thrust forces and torque based on radial basis function network (RBFN)**

Neural network based on localized basis functions and iterative function approximation are referred to radial basis function network (RBFN). Compared with Artificial Neural Network and Back Propagation Neural Network, Radial Basis Function Neural Network (RBFN) has reliable precision, simpler structure, and fast learning speed. In essence, RBFN is a system network to dynamically establish the relationship between input with output. As shown in Figure 8, it includes three network layers: the input layer serves as a signal transmission; the task of the hidden layer is different from output, whereas the learning strategies between them are different. The output layer was used to adjust the linear weights, which is the linear optimization strategy. The hidden layer was set up to adjust to parameters of the activation function (Gaussian, usually) with the non-linear optimization.

The input data of RBFN is an N-dimensional vector that connects to the hidden layer. The common form of the transfer function in the hidden layer is the Gaussian (radbas) shown in equation (4).

$$\text{radbas}(n) = e^{-n^2}$$  \hspace{1cm} (4)

where $n$ is the input signal and reaches the maximum at the origin.

The output data of RBFN is connected to all neurons of the hidden layer as shown in equation (5).

$$Y = \text{radbas}(\|\omega - X\|b)$$  \hspace{1cm} (5)
where $X$ is the input data of RBFN, $\omega$ is the weight vector with the same dimension with $X$, $b$ is the threshold value of Gaussian function.

RBFN is a process of learning and iteration until the root mean square error (RMSE) reaches an acceptable value. The learning data and input data based on the $L_{27}$ orthogonal array are shown in Table 6. After adjusting and testing the RBF model repeatedly, it showed an excellent precision when the hidden neuron number set as 25, the initial weighting set as 0.6, the learning rate is 0.001, and iterations were 450.

To validate the precision of present RBFN model, the predicted and experimentally measured filling thrust force and torque were discussed and compared. In this work, two adult teeth were used to test the predictive ability based on RBFN. The shape and parameters of teeth was obtained by CT Scanning (JIATENG, JTVMS2010, China). The filling parameters used in the confirmation tests are shown in Table 7. The results of confirmation tests and comparison with the RBFN model were shown in Table 8. The results showed a better predictive accuracy of the RBFN model for the thrust forces and torque. Furthermore, in order to illustrate the accuracy, we conducted the comparison between RBFN and ANN with experimental results. Specifically, the force values were predicted with the "logsig"-"purelin" ANN using MATLAB toolbox. And the comparison between RBFN, ANN, and experiments is shown in Figure 9. It can be concluded that during the straight canal preparation, ANN and RBFN have the similar predictive error (less than 15%), although RBFN performs a little better (around 10%). However, during the preparation in curved canals and real teeth, it can be found that RBFN has an

### Table 6. Input parameters of $F_1$, $F_2$, and $M$.

| Input of thrust force 1 | Input of thrust force 2 and torque |
|------------------------|-----------------------------------|
| A | B | C | A | B | C | D |
| --- | --- | --- | --- | --- | --- | --- |
| 0.35 | 0.20 | 15 | 0.35 | 0.20 | 15 | 30 |
| 0.35 | 0.20 | 20 | 0.35 | 0.20 | 20 | 40 |
| 0.35 | 0.25 | 15 | 0.35 | 0.25 | 15 | 50 |
| 0.35 | 0.25 | 20 | 0.35 | 0.25 | 20 | 60 |
| 0.35 | 0.25 | 25 | 0.35 | 0.25 | 25 | 80 |
| 0.35 | 0.30 | 15 | 0.35 | 0.30 | 15 | 50 |
| 0.35 | 0.30 | 20 | 0.35 | 0.30 | 20 | 60 |
| 0.35 | 0.30 | 25 | 0.35 | 0.30 | 25 | 70 |
| 0.40 | 0.20 | 15 | 0.40 | 0.20 | 15 | 40 |
| 0.40 | 0.20 | 20 | 0.40 | 0.20 | 20 | 50 |
| 0.40 | 0.25 | 15 | 0.40 | 0.25 | 15 | 50 |
| 0.40 | 0.25 | 20 | 0.40 | 0.25 | 20 | 60 |
| 0.40 | 0.30 | 25 | 0.40 | 0.30 | 25 | 80 |
| 0.50 | 0.20 | 15 | 0.50 | 0.20 | 15 | 50 |
| 0.50 | 0.20 | 20 | 0.50 | 0.20 | 20 | 60 |
| 0.50 | 0.25 | 25 | 0.50 | 0.25 | 25 | 80 |
| 0.50 | 0.30 | 15 | 0.50 | 0.30 | 15 | 70 |
| 0.50 | 0.30 | 20 | 0.50 | 0.30 | 20 | 80 |
| 0.50 | 0.30 | 25 | 0.50 | 0.30 | 25 | 90 |

### Table 7. Cutting condition in confirmation tests with human teeth.

| Test | Diameter of instrument (mm) | Width of root canal (mm) | Feed rate (mm/min) | Curvature of root canal (°) |
|------|-----------------------------|--------------------------|-------------------|-----------------------------|
| 1    | 0.35                        | 0.27                     | 15                | 37                         |
| 2    | 0.40                        | 0.27                     | 20                | 37                         |
| 3    | 0.35                        | 0.32                     | 15                | 43                         |
| 4    | 0.40                        | 0.32                     | 20                | 43                         |
excellent performance (error less 15%) than ANN (error more than 25%). It can be presumed that the error exists in ANN results from two reasons: firstly, the variety structures of teeth (nonlinear variation) lead to a challenge to the ANN model which is designed in the prediction of linear data based on the Purelin function. Secondly, the large diameter NiTi files produce more cutting debris because the drastic contact between NiTi file and root canal compared with the smaller one. Therefore, the great changes of NiTi file are more likely to influence the process, which leads to the nonlinear factors of predictive process.

Table 8. Results of confirmation tests and comparison with RBFN model.

| Test | Experimental values |       | Prediction values with error |       |
|------|---------------------|-------|-----------------------------|-------|
|      | F₁ (N)  | F₂ (N)  | M (N mm) | F₁ (N)  | Error (%) | F₂ (N)  | Error (%) | M (N mm) | Error (%) |
| 1    | -1.79    | 3.07    | 0.42   | -1.89  | -5.59     | 3.48    | -13.36  | 0.37     | 11.90    |
| 2    | -1.62    | 4.59    | 0.49   | -1.75  | -8.02     | 5.08    | -10.68  | 0.45     | 8.16     |
| 3    | -1.42    | 2.64    | 0.38   | -1.55  | -9.15     | 2.78    | -5.30   | 0.33     | 13.16    |
| 4    | -1.47    | 4.20    | 0.59   | -1.62  | -10.20    | 4.55    | -8.33   | 0.54     | 8.47     |

Figure 9. Comparison of thrust force and torque between experiments with prediction: (a) thrust force of F₁, (b) thrust force of F₂, and (c) torque.

Conclusions

In this paper, an in vitro experimental platform of canal preparation process to measure force and torque has been established. This platform allows customization of samples and feed motion. Based on the experimental results, the analysis of S/N ratio and ANOVA was conducted to obtain the weight of influence of different factors. The optimization of preparation process was proceeded via the analysis results. Besides, a radial basis function network (RBFN) model was established to predict the thrust force and torque in a wider range of parameters. Clinically, the proposed model can be
applied to instruct the dentists during root canal preparation and to improve the geometrical design of nickel titanium files. Based on the work performed, the following conclusions can be drawn:

- An experimental platform was established to measure the thrust force and torque during root canal preparation. The platform supports various experiments with different size of root canals and feed motion.
- A root canal preparation model based on ANOVA and RBFN is established. It can be indicated that the proposed model has an accurate precision in the force and torque prediction (error less than 14%). Furthermore, for dentists, the diameter of NiTi file and the feed rate below the suggested range should be used for the root canal with large width and small curvature clinically.

**Author contributions**

Weihao Guo: Conceptualization, methodology, formal analysis, writing – original draft, writing – review and editing, visualization. Liming Wang: Conceptualization, methodology, funding acquisition, formal analysis, writing – original draft – review editing, supervision. Jianfen Li: Conceptualization, methodology, funding acquisition, formal analysis, writing – original draft, writing – review and editing. Wenxiang Li: Investigation, resources, writing – review and editing. Fangyi Li: Conceptualization, methodology, funding acquisition, formal analysis, writing – original draft, writing – review and editing. Yu Gu: Conceptualization, methodology, funding acquisition, formal analysis, writing – original draft, writing – review and editing.

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