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Influence of Instrument Kinematics on Forces and Vibrations During Root Canal Shaping

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Abstract
The dental structures experience stress during root canal instrumentation, and patients feel pain from both the instrument vibrations and the applied forces. The research evaluated three endodontic files based on their kinematics to determine which system delivered the best results for minimising treatment errors and achieving optimal outcomes between the 2Shape, WaveOne Gold (WoG), and Self-Adjusting File (SAF). The sample teeth have been mounted on cement blocks padded with a silicon layer to mimic the original condition, while they were intact with the jaw. The system received continuous mechanical feedback during the three endodontic file preparation process of the sample teeth. The precision dynamometer tracked the cutting forces which occurred during instrumentation while the accelerometer measured the vibrations that each file produced. The system enabled us to track file performance during our complete shaping work process. The data analysis suggests, the SAF system applied the lowest force among all three instruments, which resulted in less mechanical stress on root structures. The 2Shape system produced the lowest vibration signals compared to all other tested instruments, which could minimise patient discomfort during root canal treatment. The research demonstrates that SAF technology enables superior force control for dental structure protection, yet 2Shape instruments less vibrations. The selection of instruments depends on clinical needs because clinicians need to decide between instruments that use minimal force and instruments that produce less vibration. The presented research provides evidence for endodontic instrument selection, which helps dentists achieve better treatment results through tooth preservation and patient satisfaction improvement.

Keywords- Endodontic Files, Ni-Ti instruments, Shaping force, Dentine fractures, Vibrations, Forces, Ex-vivo analysis, Dental instruments, Kinematics.

1. Introduction

The endodontic procedure requires dentists to use instruments which extract infected or impaired tissue from the root canal. The root canal shaping instruments produce forces and vibrations which may compromise the entire procedure's success.

The endodontic instrument experiences stress from force application during shaping until its torsional strength reaches its maximum point and it fails (Arias et al., 2014). The situation becomes challenging because dental professionals need to perform additional procedures to remove broken instrument from the root canal (Meidyawati et al., 2019).

The response of endodontic files to force depends on their specific design (Arias et al., 2014; Meidyawati et al., 2019). The application of excessive force during root canal procedures can result in file breakage, bending, and file entrapment within the canal. Force is generated when the file removes dentin from root canal walls. Sometimes the force leads to unsuccessful cleaning and shaping of the canal (Omori et al., 2022). The application of excessive force during root canal procedures results in two possible outcomes which produce either ledges or transportation that prevents complete canal filling (Shantiaee et al., 2019). The success of endodontic files depends on dentists who use precise force application to achieve their best results.

Research studies have analyzed root canal shaping results through their examination of procedural forces and reaction torque (Jafarzadeh and Abbott, 2007; Kwak et al., 2022). The researchers used finite element models to study how tooth and instrument impact the complete process (Carpegna et al., 2020; Kwak et al., 2022; Martins et al., 2022). The endodontic file operates through its central axis rotational movement to extract dentin and pulp tissue from root canals. The file moves towards the apex of the root canal, it bends to adopt the curvilinear shape of the root canal (Carpegna et al., 2020). The curved design of the instrument creates continuous stress at bent part of instrument that makes it more susceptible to fatigue-related breakdown (Omori et al., 2022). The failure of endodontic files during root canal preparation happens when two particular situations occur: when the canal dimensions become too small and when users apply excessive force and twisting pressure during the shaping process (Silva et al., 2023; Unno et al., 2022). Currently, there are limited findings and methods available to avoid instrument separation in root canal shaping. Some files, however, have a lower probability of separation (Ikogou, 2023), hence, if the way to predict possible file separation is changed, endodontists could provide smoother treatment.

In addition to file separation, using too much shaping force during root canal treatment might affect effectiveness and efficiency of the instrument. Research indicates that this situation produces three possible results, which include vertical root fracture, microcrack formation and patient discomfort (Choi et al., 2017; Miguens-Vila et al., 2017). Ni-Ti instruments unbalanced forces which may produce severe vibrations that lead to root fractures and craze line development (Jamleh et al., 2016; Tonelli et al., 2021). The development of small cracks and craze lines in teeth results in tooth fractures according to Tonelli et al. (2021). Endodontists have studied the patterns of root canal shaping forces because they need to understand their strength and treatment effects (Kwak et al., 2022; Medha et al., 2014; Nayak et al., 2018, 2019; Omori et al., 2022).

The study by Thakur et al. (2022) used ANSYS to develop finite element models of endodontic instruments that were used for root canal instrumentation. Thakur et al. (2022) studied three NiTi alloy instruments for canal preparation through mechanical behaviour assessment, which showed the TS1 file produced the highest total deformation and equivalent elastic strain compared to TS2 and WOG files.

The study by Ha et al. (2023) demonstrates how screw-in force affects endodontic instrument performance. The research by Ha et al. (2023) investigates how screw-in force affects endodontic instrument performance. leads to iatrogenic errors that cause instrument penetration beyond the root canal apical foramen. The rotary instrument uses its helical cutting blades that work as screw threads to generate apical force during rotation (Ha et al., 2023) in the apical direction. The treatment process becomes compromised when the instrument extends past the apical foramen because it causes root crack formation, apical transportation, taper lock effect and apical foramen enlargement (Kwak et al., 2019). The instrument needs proper control to stop iatrogenic errors from occurring during the shaping procedure.

Root canal files' performance and longevity may be impacted by their shaping force. Numerous reasons for the breakage of NiTi, like reaction torque, pushing and cyclic motion of the endodontic instrument in apical direction, cyclic loading that causes fatigue failure, the design of the instrument, and the shaping technique employed for root canal shaping (Kim et al., 2010).

A rotary unbalanced mass caused vibration in a system. The motion of the rotating parts during root canal shaping may result in vibration. As Choi reported (Choi et al., 2017) in their article, vibration can help in initiating minor cracks in the root of the tooth or it may cause significant fracture of the root, sometimes it may lead to the instrument separation. Such spinning components are part of the endodontic motor and its contra-angle handpiece, including the endodontic file, gears, the handpiece's transmission shaft, and the motor's rotor and shaft. Vibration at the rotational frequency and its harmonics can be produced by any imbalance in their mass. Furthermore, compared to its rotating motion, the motor's reciprocating mode can produce stronger vibrations.

Even though many endodontic files with varying geometries and kinematics have been developed in recent decades, problems with instrument separation, dentine fractures, root fractures, and root canal shape remain unresolved (Ha et al., 2023; Kwak et al., 2019). For further understanding the shaping capability of different endodontic instruments was analysed. On the other hand, a more quantitative approach to analysis could produce better outcomes. Similarly, a novel mechanistic approach based on physical analysis is presented by Wang et al. (2022) to forecast thrust force during root canal preparation. The cutting simulation (CS) algorithm is a computer-based simulation that helps to unveil the interaction between the instrument and the root canal geometry. The literature indicates that during the virtual simulation of using the CS algorithm, the model exhibited a mean difference of approximately 20% between the predicted value using the algorithm and the experimental results. The device lowers thermal and physical damage to root canals by improving thrust prediction (Wang et al., 2022).

The root canal shaping process generates vibration because the file moves through the canal at different speeds, which produce multiple frequency patterns and amplitude levels. The periodontal involvement causes teeth to become more mobile, which makes the uncomfortable sensation worse. The combination of dental equipment sounds and vibrations in endodontics causes hand-arm vibration syndrome and simultaneously leads to iatrogenic enamel cracking and dentin damage, which results in higher patient stress levels (Choi et al., 2017). The goal should be to reduce all three elements of vibration and force and noise because they cause patient discomfort.

The prevention of root perforation and instrument separation, and dentinal microcracks during root canal treatment requires dentists to use minimal force when shaping canals. The presented research used ex vivo experimentation to evaluate the performance of three Ni-Ti file systems with different kinematic movements during root canal preparation. The research tracked both the force applied to the apex and the instrument-produced vibrations that occurred throughout the procedure. The research measured mechanical outputs to gain insight into file behaviour and performance during actual clinical procedures.

The remainder of this paper is organised as follows. Section 2 describes the materials, experimental setup, and methodology employed for evaluating the forces and vibrations generated during root canal shaping using three different endodontic file systems. Section 3 presents the results of force and vibration analyses derived from ex-vivo experiments, followed by the statistical evaluation of the findings. Section 4 discusses the implications of the observed trends, compares the outcomes with previous in-vitro studies, and highlights factors influencing experimental variability. Finally, Section 5 summarises the key conclusions and provides practical recommendations for clinicians regarding instrument selection and clinical application.

2. Materials and Methods

We used human maxillary molars, which were obtained for unrelated purposes as experimental specimens. The teeth were kept in a 0.1% Thymol solution from the start to their utilisation in the study to maintain their structural integrity. We conducted a radiographic evaluation of all specimens through mesiodistal and buccolingual imaging before acceptance to confirm their eligibility. The chosen teeth showed complete apical closure with their complete coronal and radicular structures remaining healthy and free from disease. The radiographic assessment proved the specimens suitable for study by showing no signs of fracture lines or resorptive changes or secondary mineralisation, or structural defects. We used strict selection criteria to create a uniform study group, which included only specimens that had matching anatomical features (Nayak et al., 2021). The research design used randomisation to place specimens into three treatment groups, which included WaveOne Gold (WoG) and Self-Adjusting File (SAF) and 2Shape (TS) systems. Cement blocks have been created with embedded teeth using 3D printed boxes of equal dimensions. Additional silicone has been applied as a thin coating between the cement block and tooth to create a simulation of natural damping effects (**Figure 1**). Then, force and vibration tests have been performed using three different kinematics endodontic files after they completed the root canal access cavity preparation of the embedded tooth.

Three endodontic file systems have been used with different kinematic designs to study how instrument movement affects both force output and vibration intensity. The WaveOne Gold (WoG) system achieves its operation through a particular back-and-forth movement, which enables users to advance the instrument to the apex while minimising torsional stress. The Self-Adjusting File (SAF) operates through a trans-linear oscillating motion which produces controlled vibrations at 5000 cycles per minute. The 2Shape system runs in continuous clockwise operation while users can adjust taper and cross-sectional design to boost its cutting ability. The three main kinematic approaches in modern endodontic instrument include reciprocation, oscillation and rotation, which allow researchers to study their mechanical effects on root canal preparation. The different motion patterns used in endodontic procedures affect both instrument stress distribution and patient comfort, cutting efficiency, and debris removal during root canal preparation.

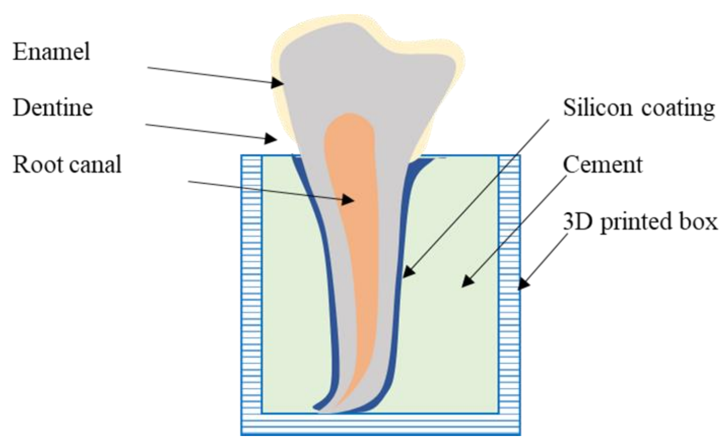

Figure 1. Sample tooth mounted on the cement block.

The experimental procedure used a precision bench vice to hold tooth specimens in place during root canal shaping. The Dytran 3093B accelerometer is mounted on the instrumentation stud to record vibrational signals, as shown in **Figure 2**. The Kistler dynamometer provided force measurements while the accelerometer recorded vibration data at the same time. The accelerometer contains a shear-mode sensing element which produces low impedance readings. The sensor design includes features which decrease noise levels and minimize its reaction to environmental factors including temperature changes and mounting stress. The accelerometer design allows it to detect vibrations at different frequency ranges which makes it suitable for experimental work that needs to measure both low and high frequencies. The instruments sent their output signals to a Data Acquisition system, which digitised and transformed the analogue data into force and vibration measurements. The computer received digitised data, which it used to display and store the information. The dynamometer operated at 7142 Hz while the accelerometer operated at 51200 Hz to obtain suitable signal characteristics. A custom MATLAB program executed post-acquisition signal processing and feature extraction operations on the recorded data.

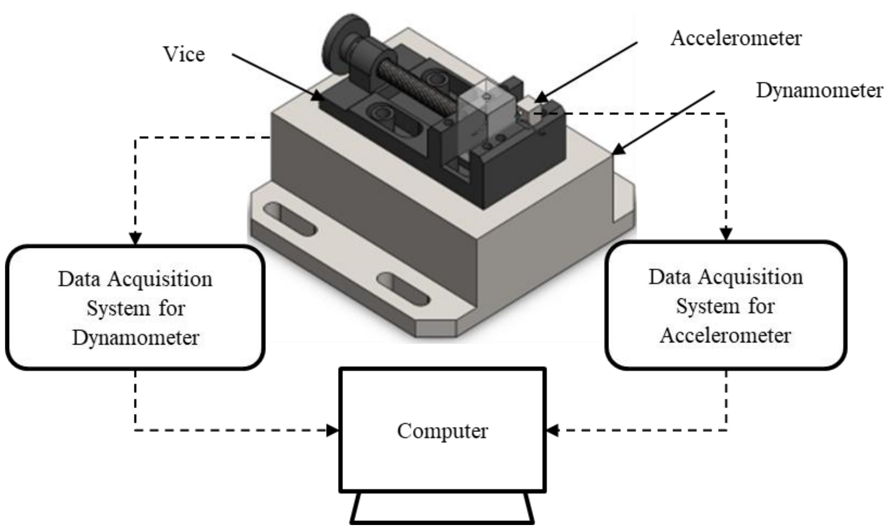

Figure 2. Diagram showing the experimental setup.

The selected teeth were then randomly assigned to three different experimental groups, each corresponding to one of the file systems that are evaluated. These groups were designated names as the 2S group, the WoG group, and the SAF group. Post grouping, the root canal shaping was performed for each group. To ensure comparability, a WaveOne motor (WOM, Dentsply Maillefer) that had undergone testing was used for all three sets of files. A practitioner who has practiced endodontics for more than ten years performed the root canal instrumentation by using fresh files for each canal and distilled water for irrigation.

The 2Shape rotary system (Micro-Mega, France) operated through the sequence provided by the manufacturer. The process of canal shaping began with #10K and #15K stainless-steel hand files to create a glide path before using TS1 and TS2 instruments under controlled speed and torque settings with continuous clockwise rotation. The standardized mechanical preparation process was applied to all samples through this method.

The WoG group underwent canal shaping through the WaveOne Gold file which operated under a dedicated reciprocating motor (WOM) with a 1:6 reduction handpiece. The WaveOne Gold file operated at its recommended reciprocation cycle and torque settings to maintain its cutting performance and extend its operational life.

The SAF needed activation through a ReDent Nova handpiece head (Ra'anana, Israel), which functioned as a vibrating tool. The device produced 0.4 mm oscillations at 83.33 Hz to enable the file to match three-dimensional canal shapes. The process of canal scouting with a #20K hand file (Dentsply Maillefer) occurred before SAF activation to establish both patency and working length.

The instrumentation process recorded both force and vibration data, which were used to calculate RMS values for stress measurement during canal shaping. The three file systems received evaluation through signal analysis of their mechanical stresses.

The root mean square (RMS) statistical measure calculates time-dependent signal strength to deliver essential data about vibration intensity. The RMS values from recorded signals enabled researchers to measure the complete signal power throughout all experimental conditions. The RMS functions as a useful measurement because it shows signal power levels without being influenced by intermittent peak events, which are caused by random body movements or short interruptions during canal shaping.

2.1 Statistics and Data Analysis

The research used six sets of teeth during its pilot study. The pilot study data allowed us to determine the needed sample size through Operating Characteristic (OC) Curves. An operating characteristic (OC) curve shows the performance level of statistical tests and quality control procedures based on their critical parameters and decision criteria. The Operating Characteristic Curve shows how test power affects Type I and Type II error rates through its connection to the chosen significance level.

Statistical tests achieve higher power because they successfully detect and confirm false null hypotheses. The significance level serves as an indicator of how likely it is that a statistical test will mistakenly reject a null hypothesis that is true. The operating characteristic (OC) curve demonstrates how test power changes when researchers modify their decision criteria or critical values. The graphical representation helps researchers understand how test adjustments affect both the detection of real effects and the production of false positive results.

The OC curve is a very useful tool to determine the size of sample to realize a required power for a statistical test of a given effect size or treatment difference. The adequate sample size is the key to minimising the type II error, which helps to make the study design more responsive to potential variations between the treatments.

Table 1. Comparison of the RMS measurement of force (N) and vibration (m/sec^2) generated by three experimental groups.

Scheme	File	WoG	SAF	TS	
				TS_1	TS_2
Ex-vivo	Mean ± SD of the RMS of the force signal	2.826±1.00	1.152±0.100	1.217±0.60	1.687±0.50
	Mean ± SD of the RMS of the vibration signal	0.229± 0.04	0.211± 0.04	0.055± 0.019	0.062± 0.01
In-vitro (Nayak et al., 2019)	Mean ± SD of the RMS of the force signal	0.915±0.26^{x}	0.410 ±0.08^{z}	0.528±0.13^{y,z}	0.688±0.16^{y}
	Mean ± SD of the RMS of the vibration signal	0.203±0.036^{a}	0.156±0.05^{b}	0.050±0.02^{c}	0.070±0.01^{c}

According to the preliminary findings, there is a likelihood of at least 0.90 to reject the null hypothesis. **Table 1** displays the means of the various groupings. We now take into consideration $\alpha = 0.05$ for additional analysis.

$$\tau = \mu_n - \bar{\mu} \tag{1}$$

$$\bar{\mu} = \frac{\sum_{i=1}^{n} \mu_i}{a} \tag{2}$$

$$\varphi^2 = \frac{n \sum_{i=1}^{n} \tau_i^2}{a\sigma^2} \tag{3}$$

The standard deviation of force amplitude (σ) appears in Equations (1-3), while a represents the number of study groups (four in this case) and μ_n shows the mean value of the n^{th} group. It is expected that each group's standard deviation cannot be more than σ = 1N. The type II error β of the experiment can be computed using Equations (1-3) and the experimental data displayed in **Table 1**. To estimate the type II error using the OC curve, we took into account n (number of repeats) = 10 to 14. **Table 2** shows the estimation of the power of the test corresponding to the experimental conditions.

Table 2. Estimated sample size for root canal shaping performed with three endodontic files operating under different kinematics.

n	φ^2	φ	$a(n-1)$	$\approx\beta$	Power (1-β)
10	4.50	2.12	36	0.07	0.93
11	4.95	2.22	40	0.05	0.95
12	5.40	2.32	44	0.04	0.96
13	5.85	2.42	48	0.03	0.97
14	6.30	2.51	52	0.01	0.99

The preliminary power analysis in **Table 2** showed that the initial experiment with ten specimens did not meet the required statistical sensitivity threshold. The current sample size of ten specimens creates a high risk of Type II errors because it fails to detect actual treatment effects. The power of statistical analysis becomes stronger when the number of specimens is increased. The experimental sensitivity needed more specimens to be tested in order to produce improved results.

The power calculations in **Table 1** show that adding 11 to 14 specimens will reach the desired power level for this research. The experimental design becomes better at finding real differences between groups when the number of specimens is in this range because it reduces the risk of Type II errors.

The vibrational analysis needed to assess all specimens because it ran simultaneously with the testing process. The minimum number of replicates needed for vibration characterisation appears in **Table 3** based on RMS vibration signatures for the three experimental groups. The analytical framework established the number of replicates needed for all treatment conditions through its calculation of σ = 0.05N as the standard deviation for RMS value differences between groups.

Table 3. Sample size estimation for root canal preparation to achieve relevant test power for endodontic files of different kinematics.

n	φ^2	φ	$a(n-1)$	$\approx\beta$	Power (1-β)
10	229.63	15.15	36	>0.01	>0.99
11	252.59	15.89	40	>0.01	>0.99
12	275.55	16.60	44	>0.01	>0.99
13	298.51	17.28	48	>0.01	>0.99
14	321.48	17.93	52	>0.01	>0.99

11 to 14 duplicates are adequate for this experiment, according to the analysis based on operating characteristic curves. Consequently, it has been determined that the sample size for this experiment will be *n* = 14.

Experiments have been repeated to fulfil the replication requirements for each group (*n* = 14). This means that each group was subjected to the same experiment multiple times to ensure that the results were consistent and reliable.

During the experimentation, in order to ensure that the results were comparable to the earlier experiment and followed the same protocol previously discussed, the same procedures, equipment and experimental conditions were followed.

Once the experiments were completed, the output data of the vibration and fore signals for each experimental group was gathered. This data was analysed by the researchers using the ANOVA (Analysis of Variance) approach.

The statistical method of one-way analysis of variance (ANOVA) helped to perform comparative analysis of data between multiple groups through mean value analysis. The method determines if the group means show significant differences from each other. The two essential requirements for ANOVA analysis include normal distribution of data and equal variances between groups. The ANOVA test evaluates group variance differences through the F-ratio calculation, which determines if mean differences reach statistical significance. The F-ratio shows statistical significance when the null hypothesis is rejected, which indicates that the group means demonstrate substantial differences. The significant difference between the groups was analysed with the help of ANOVA (one-way). The analysis of the RMS values of the signals received during root canal shaping was performed. Tukey test has been executed to test the difference among groups by keeping the confidence interval at the 95%.

3. Results

The patterns for the vibration signals and the force signals for the three-file system for ex vivo analysis are displayed in **Figures 3** and **4**. The identical pattern seen in the ex-vitro analysis is shown in each figure. The mechanical responses of endodontic file systems during canal shaping appear in **Figure 3**. The mechanical response of instruments during the procedure becomes visible through these plots which show different cutting resistance levels and load distribution patterns. The vibration signals from endodontic instruments during ex-vivo testing appear in **Figure 4**. The vibration traces from the files show their dynamic behavior through motion characteristics and operational stability differences between the three kinematic systems.

To check whether the three types of files produce any meaningful differences in force or vibration, an ANOVA test is used. The starting assumption, or null hypothesis, is that all three groups behave the same and show no real difference. This is tested at a 5% significance level. The F-test helps compare the variation within each group to the variation between the groups. If the calculated F-value turns out to be higher than the critical value for the 5% level, the null hypothesis is rejected, suggesting that at least one of the file systems performs differently from the others.

The investigation looked at the force and vibration responses of four groups WoG, SAF, TS1 and TS2—using a one-way ANOVA. After examining **Table 4** for the results of that analysis. The RMS values of the force signals showed differences among the values of the four groups. The between-group sum of squares was 41.332. That number explains that the mean of the group differs in a way. The computed sum of squares (within-group) is 18.137, which represents the level of variability present among the data points inside each group. If we compare it with the sum of squares calculated between groups, then it is found considerably larger, showing that the groups differ markedly from one another. This significant gap tells us that the variation in RMS value between different experiments is much smaller than the difference in signal RMS value we compare it among the groups.

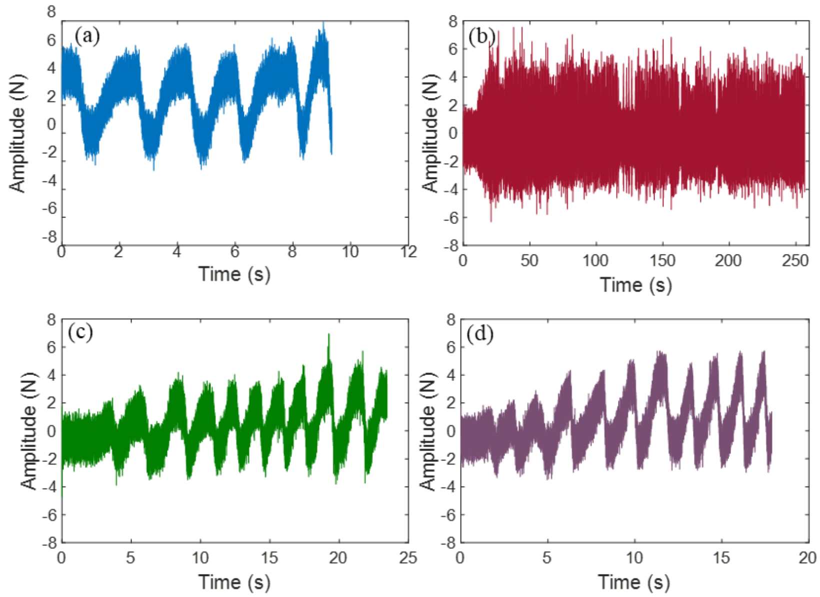

Figure 3. Representative patterns of the force signals recorded during root canal shaping with (a) WoG, (b) SAF, (c) TS1, and (d) TS2.

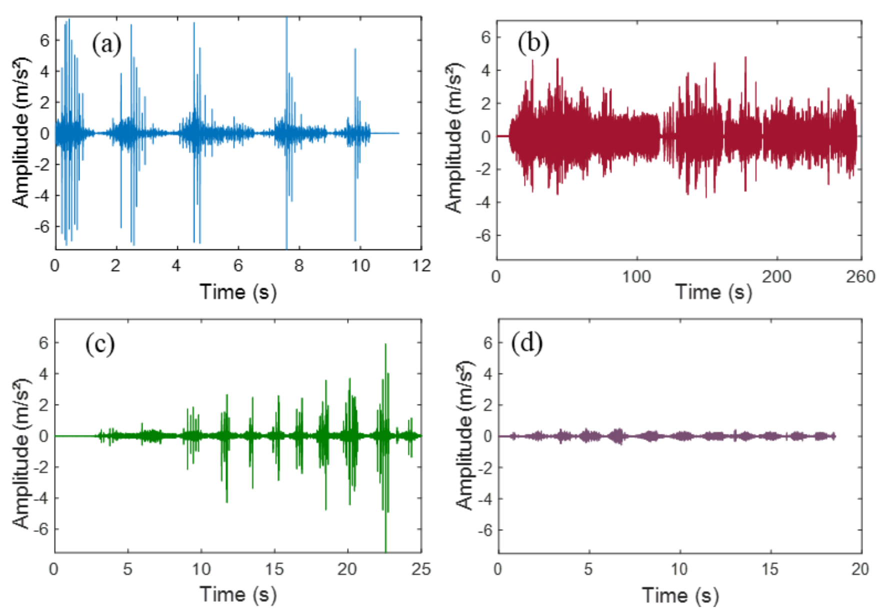

Figure 4. Representative patterns of the vibration signals recorded during root canal shaping with (a) WoG, (b) SAF, (c) TS1, and (d) TS2.

Table 4. One-way ANOVA calculated results.

Parameter	Category	Sum of squares	Degrees of freedom	Mean square	F-value	Significance
RMS value of the force signal (N)	Between Groups	41.33	3	13.78	39.5	<.001
	Within Groups	18.13	52	0.35		
	Total	59.47	55			
RMS value of the vibration signal (m/s^2)	Between Groups	0.34	3	0.11	80.05	<.001
	Within Groups	0.07	52	0.001		
	Total	0.41	55			

In the ANOVA results, the variation between the four file systems is associated with 3 degrees of freedom, while the variation within the groups is linked to 52 degrees of freedom. These values reflect how the total variability in the dataset is divided. When we compare the mean square between groups (13.777) with the much smaller mean square within groups (0.349), it becomes clear that the differences in the group averages are far larger than the random variation expected inside each group. This strongly suggests that the four file systems do not behave the same and that the differences observed in their force measurements are meaningful rather than coincidental.

The vibration data reinforces this conclusion. The one-way ANOVA performed on the vibration signals also showed a noticeable separation among the four groups. The total sum of squares (0.41) indicates that the vibration values vary across all samples. Out of this total variability, a substantial portion—represented by the sum of squares between groups (0.34)—is due to differences among the file systems themselves. The corresponding F-value of 80.05 is extremely high and far exceeds the value for a 5% significance level. This means the probability of observing such large differences by chance is very small. In other words, the vibration responses of the four file systems are statistically distinct, confirming that each system behaves differently during root canal shaping.

Table 5. Results for Tukey's post hoc analysis between-group comparisons.

Dependent variable	(I) Name	(J) Name	Mean difference (I-J)	Standard error	Significance	95% Confidence interval	
						Lower Bound	Upper Bound
Force	WoG	SAF	1.95848*	0.223	<.001	1.366	2.551
		TS1	2.16131*	0.223	<.001	1.569	2.754
		TS2	1.74368*	0.223	<.001	1.151	2.336
	SAF	WoG	-1.95848*	0.223	<.001	-2.551	-1.366
		TS1	0.20283	0.223	0.8	-0.390	0.795
		TS2	-0.2148	0.223	0.771	-0.807	0.378
	TS1	WoG	-2.16131*	0.223	<.001	-2.754	-1.569
		SAF	-0.20283	0.223	0.8	-0.795	0.390
		TS2	-0.41764	0.223	0.253	-1.010	0.175
	TS2	WoG	-1.74368*	0.223	<.001	-2.336	-1.151
		SAF	0.2148	0.223	0.771	-0.378	0.807
		TS1	0.41764	0.223	0.253	-0.175	1.010
Vibration	WoG	SAF	0.01187	0.014	0.836	-0.026	0.049
		TS1	0.16956*	0.014	<.001	0.132	0.207
		TS2	0.15072*	0.014	<.001	0.113	0.188
	SAF	WoG	-0.01187	0.014	0.836	-0.049	0.026
		TS1	0.15769*	0.014	<.001	0.120	0.195
		TS2	0.13886*	0.014	<.001	0.101	0.176
	TS1	WoG	-0.16956*	0.014	<.001	-0.207	-0.132
		SAF	-0.15769*	0.014	<.001	-0.195	-0.120
		TS2	-0.01884	0.014	0.547	-0.056	0.019
	TS2	WoG	-0.15072*	0.014	<.001	-0.188	-0.113
		SAF	-0.13886*	0.014	<.001	-0.176	-0.101
		TS1	0.01884	0.014	0.547	-0.019	0.056

* The mean difference is significant at the 0.05 level.

Tukey's *post-hoc* analysis was used to identify groups that substantially differed from one another. **Table 5** shows the outcomes of Tukey's *post-hoc* analysis. The one-way ANOVA results show that the four groups have different mean values because they exhibit a statistically significant difference between their means.

As shown in **Table 5**, the WoG system generates noticeably higher apical force compared with the TS1 and SAF instruments during canal shaping. This suggests that the kinematic motion and design characteristics of the WoG file may contribute to increased downward force while advancing toward the apex. The statistical assessment of the data also indicates that the RMS force values among all three file systems differ significantly, meaning their overall force patterns are not comparable. Despite this general difference, the analysis shows that the RMS force values for the TS2 and WoG instruments are statistically similar, indicating that these two systems produce comparable force magnitudes under the testing conditions.

The results from **Table 5** show that the force signature RMS mean value patterns match the findings of Nayak et al. (2019) in their in-vitro study. The 95% Confidence Interval of Tukey's test for statistical analysis shows the mean RMS value variation of force and vibration signatures between three different instruments. The WoG instrument produces stronger apical forces than the TS1 and SAF instruments, according to the study. The TS instrument produces a mean RMS value that is significantly lower than the WoG and SAF instruments, yet these instruments generate identical vibration patterns.

The results match the results from the in-vitro study. The results show that the SAF instrument delivers lower forces than the WoG instrument but both instruments generate higher vibration levels than the TS instrument.

Additionally, the Tukey simultaneous test (**Table 5**) demonstrates that the TS1 and TS2 instruments perform nearly identically.

4. Discussion

Both the ex-vivo and in-vitro experiments' results follow the same general pattern (Nayak et al., 2019). However, because of the tooth's and the endodontic blocks' material characteristics, the mean RMS values' magnitudes varied. It can be seen from the ex-vivo study's results (**Table 1**) that the RMS values' standard deviation is higher than that of the ex-vitro study's RMS values (Nayak et al., 2019). The non-uniform anatomy of the sample teeth is the primary reason for the large standard deviation. The chosen tooth, however, had almost identical architecture for the sake of the experiment; yet, slight differences in tooth density and anatomy would result in different signal amplitudes. Although increasing the sample size helps reduce the experimental error, getting a lot of teeth extracted is still a difficult task. Therefore, in this study, the sample size is determined using a statistical method. Furthermore, the tooth's density and hardness differ from patient to patient and are not the same. Therefore, obtaining a limited standard deviation of the data is usually a difficult challenge.

The data in **Table 1** shows that root canal shaping under ex-vivo conditions generates higher forces and vibration amplitudes than in-vitro testing. The natural tooth properties in ex-vivo models produce stronger mechanical responses than the controlled in-vitro tests. The tooth's hardness is the cause of this. The tooth's hardness is marginally higher than the acrylic block's (Nayak et al., 2019). The material dislodging force outperformed the endodontic block in-vitro test results, according to the ex-vivo study. Ex-vivo root canal shaping produces larger vibration amplitudes due to the material dislodging force than in-vitro root canal shaping.

The research used three different kinematic endodontic files which included a reciprocating file and a rotary file and a trans-line motion file. The research evaluated instrument force output and vibration levels from each of the tested instruments. The research established that endodontic instrument force and vibration output depends on their design geometry and motion patterns which affects clinical practice. The SAF system produces weaker force outputs than WoG and 2Shape systems during canal preparation which helps dentists protect teeth from vertical root fractures and dentinal micro-cracks particularly when treating weak teeth or existing restorations (Bürklein et al., 2013).

The 2Shape system produces minimal vibration which results in lower patient stress during treatment so patients need less anaesthesia. The 2Shape system provides exceptional patient care to patients with periodontal issues and loose teeth because it produces minimal vibration. The SAF system reduces mechanical stress which helps maintain more root structure while the 2Shape system decreases vibration to enhance patient acceptance of endodontic treatment. The research provides evidence-based recommendations for instrument choice between the SAF for fragile teeth and the 2Shape for patients who experience excessive vibration during treatment.

The researchers understand that the experimental procedure performed by the experimenter/dentist could lead to errors in the investigation. The study design of this study enables us to eliminate experimental errors through normalization procedures. The same person who was both the dentist and experimenter conducted all procedures throughout the research to create equal human mistakes for all test groups.

The study used an optimal number of experiments for each group to reduce errors that stem from sample size while maintaining consistent operation performance. The research method produces valid and robust results even when human errors occur during the study.

The study took place in an ex-vivo setting which might not perfectly duplicate the actual conditions found in human root canal treatments. The research data about endodontic file performance offers valuable information yet dentists need to handle this data with care because they should consult additional studies and their personal clinical experience before treating patients. Research conducted in living patients will confirm these findings to establish a full understanding of endodontic file performance during root canal preparation.

5. Conclusion

The study evaluates force and vibration responses of three endodontic file types during root canal preparation under ex vivo conditions. The current study's findings are consistent with those of the earlier investigation, which was conducted in an in vitro setting. This explains why endodontic blocks are used in endodontic file comparison investigations. The stresses and vibrations produced during canal shaping are greatly influenced by the design and operation of the endodontic instrument. The SAF system produces lower material dislodging forces because of its unique material dislodging capabilities and adaptable design compared to WoG and TS systems. The TS1 and TS2 designs minimise root canal shaping vibration because of their tapered shape and kinematic design. The research shows that the SAF and TS file systems perform better than the WoG file system for standard root canal shapes.

The self-adjusting File (SAF) required less force to shape root canals than the WaveOne Gold (WoG) and 2Shape (TS) endodontic files. The SAF file system should be considered for basic root canal shaping because it features a unique debris removal method that needs minimal force.

The TS1 and TS2 endodontic files produce minimal vibration during root canal preparation because of their unique design features and tapered shape. The TS file system provides dental practitioners with their best choice for reducing vibration during root canal procedures.

Conflict Interests

The authors declare they have no financial or personal conflicts which could affect their research work or manuscript publication.

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AI Disclosure

During the preparation of this work the author(s) used generative AI in order to improve the language of the article. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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