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Effect of Different Downward Loads and Rotational Speeds on the Removal of Gutta-Percha and Root Canal Sealer Using a Nickel-Titanium Rotary Gutta-Percha Removal System: An Ex Vivo Study

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Abstract

Effective gutta-percha/sealer removal is essential for predictable nonsurgical endodontic retreatment, but the effects of key operational parameters on nickel–titanium rotary removal instruments remain insufficiently understood. This study aimed to examine how varying downward loads and rotational speeds affect the removal efficiency and torque/force generation of the HyFlex Remover. Sixty transparent straight resin canals filled with gutta-percha and AH Plus sealer were prepared using the HyFlex Remover at two rotational speeds (400 and 800 rpm) and three downward loads (2, 3, and 4 N; $n = 10$/group). The removal rate, calculated using micro-computed tomography, as well as removal time, maximum force, maximum torque, and cumulative torque were recorded and evaluated using two-way analysis of variance with Bonferroni correction ($\alpha = 0.05$). The removal rate was consistently higher at 400 rpm than at 800 rpm ($p < 0.001$), while removal time and cumulative torque were greater at 400 rpm ($p < 0.001$). Maximum torque differed only between the 800-2 N and 800-4 N groups ($p = 0.006$). Maximum force increased with higher loads ($p < 0.001$), and at 3 N and 4 N, it was lower at 400 rpm than at 800 rpm (3 N: $p = 0.039$, 4 N: $p < 0.001$). Overall, lower downward loads reduced torque but prolonged working time, whereas higher rotational speeds shortened both working time and torque but decreased the removal rate.

Keywords: downward load; endodontic retreatment; gutta-percha; nickel–titanium rotary instruments; removal efficiency; rotational speed; torque

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1. Introduction

Root canal treatment is performed to eliminate infection within the root canal system and prevent its recurrence, primarily in cases of irreversible pulpitis and apical periodontitis. The procedure involves chemomechanical root canal preparation, integrating mechanical instrumentation to clean and shape the canal with chemical irrigation to further reduce the microbial load, followed by three-dimensional obturation to establish a hermetic seal [1].

However, when the initial root canal treatment fails—often due to inadequate disinfection or sealing resulting from the complexity of the root canal anatomy—nonsurgical retreatment is frequently indicated. Complete removal of root filling materials, mainly gutta-percha, is often challenging, but is considered essential to ensure effective cleaning, reshaping, and refilling of the canal system [2]. Incomplete removal of filling materials can compromise disinfection and negatively influence treatment outcomes, whereas excessive instrumentation may cause canal transportation or dentinal damage [3]. Various instruments, including stainless steel hand files, Gates–Glidden drills, and ultrasonic tips, have been used for gutta-percha removal but none of them has been proven entirely effective [4].

Nickel–titanium (NiTi) rotary instruments have been used to improve the efficiency and safety of gutta-percha removal during retreatment [2–4]. The superior flexibility and shape-memory properties of NiTi rotary instruments compared with those of stainless steel files allow them to better follow the original canal curvature, thereby minimizing canal transportation and dentinal stress [5]. Several studies have shown that NiTi retreatment systems remove filling materials more effectively and in less time than manual or ultrasonic techniques, supporting their use as a reliable adjunct to stainless-steel files during removal [6,7].

The HyFlex Remover (Coltene/Whaledent, Altstätten, Switzerland) is a recently developed heat-treated NiTi rotary instrument specifically designed for removing gutta-percha and sealer. This instrument is made using heat-treated C-wire, and features a tri-edge cross-section design, with a size 30/0.07 taper blade portion and a non-cutting tip [8]. Recent studies have shown that the HyFlex Remover outperforms other NiTi retreatment files, demonstrating superior buckling resistance and mechanical performance [8], producing less residual gutta-percha with reduced instrumentation time [9], and achieving higher patency with minimal alteration in bioceramic-obturated teeth [10].

Despite the advantages of NiTi instruments, they have a higher risk of fracture during retreatment than stainless steel hand instruments [10], which can be attributed to excessive torque/force generation. Frictional heat generated during removal may decrease the fatigue resistance of NiTi instruments because elevated temperatures can shift the phase composition of heat-treated NiTi alloys toward an austenite-rich state [11], which is more prone to cyclic fatigue failure [12]. Moreover, aggressive gutta-percha/sealer removal can result in debris extrusion beyond the apex [7,13], potentially causing postoperative pain or periapical inflammation [14]. Therefore, understanding how operating parameters influence NiTi instrument efficiency and mechanics is essential for improving their safety and performance.

Previous studies on NiTi systems for gutta-percha/sealer removal have mainly focused on the file design and alloy type [15]. However, operational parameters, such as applied load and rotational speed, may be important because they can affect removal efficiency and mechanical stress on the instrument and canal. Studies show that increasing downward load during NiTi rotary instrumentation reduces apical canal deviation and working time but increases the screw-in force [16,17]. The screw-in force is a self-propelling upward force that can drive the instrument deeper into the canal and have a risk of fracture [18]. However, little is known about how downward load affects gutta-percha/sealer removal with NiTi rotary files. Evidence regarding the effect of rotational speed is also limited, although studies have suggested that higher speeds reduce debris extrusion and the working time [19–21].

Therefore, this study aimed to evaluate the effects of different loads and rotational speeds on the efficiency and torque/force generation of the HyFlex Remover instrument during gutta-percha/sealer removal, using automated instrumentation in simulated straight canal models. The null hypothesis was that neither the applied load nor the rota-

tional speed would significantly affect the removal rate, removal time, or the torque and force generated during gutta-percha/sealer removal.

2. Materials and Methods

2.1. Sample Size Estimation

G*Power software (version 3.1.9.7; Heinrich Heine Universität, Düsseldorf, Germany) was used to determine the sample size required. A priori analysis of variance (ANOVA) with fixed effects, including main effects and interactions, was selected from the F-test family to reflect the two-way experimental design. The effect size was set at 0.52 based on moderate effect reported in a previous in vitro study evaluating the mechanical behavior of NiTi instruments during root canal procedures [22]. The significance level was set at 0.05, and the statistical power was set at 0.95. Considering six experimental groups, a sample size of 10 specimens per group was determined to be sufficient to detect expected differences.

2.2. Canal Preparation, Filling, and Storage

Sixty simulated straight canals in resin blocks (END3L001; Nissin, Kyoto, Japan) with a 0.2 mm apical diameter, 0.017 taper, and 14 mm length were used (Figure 1). Canal patency was confirmed using a #15 K-file (Zipperer; VDW, Munich, Germany). The canals were prepared with HyFlex EDM One File (#25/0.08–0.04 taper, 25 mm; Coltene/Whaledent), irrigated with physiological saline, and dried with paper points corresponding to the HyFlex EDM One File. The canals were then filled using the corresponding HyFlex EDM gutta-percha point (Coltene/Whaledent) and AH Plus sealer (Dentsply Sirona, Bensheim, Germany) with the single-cone technique. The specimens were stored at 37 °C in a 100% humidified incubator for 4 weeks to allow sealer setting and maturation, a protocol commonly adopted in previous in vitro studies to simulate clinical conditions prior to retreatment [23,24].

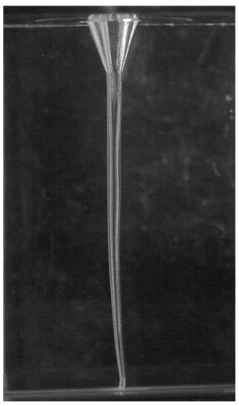


Figure 1. Representative simulated straight canal in a resin block. The canals were prepared using the HyFlex EDM One File (#25/0.08–0.04 taper) and obturated with a corresponding gutta-percha point and AH Plus sealer. After 30 days of storage, the gutta-percha and sealer were removed using the HyFlex Remover at two rotational speeds (400 and 800 rpm) and three downward loads (2, 3, and 4 N). During removal, torque, force, and working time were recorded, and the removal rate was determined using micro-computed tomography.

2.3. Micro-Computed Tomography Imaging

All specimens were scanned using a micro-computed tomography (CT) system (inspeXio SMX-100CTPlus; Shimadzu, Kyoto, Japan) at a voxel size of 0.03 mm, 70 kV, and 100 mA, with 360° rotation in 0.5° steps, frame averaging of 4, and a 1 mm aluminum filter. Three-dimensional models were reconstructed using Amira 3D 2023.2 software (Visage Imaging, Berlin, Germany) to measure the filling material volume (Figure 2).

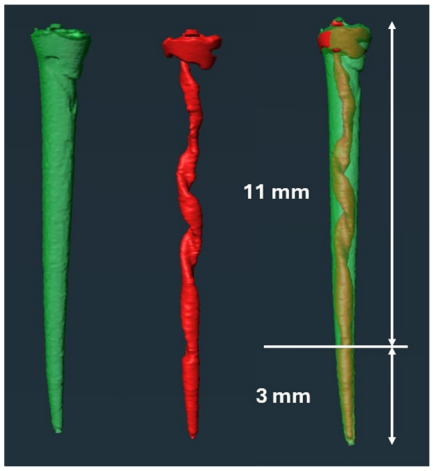


Figure 2. Representative three-dimensional reconstructed micro-CT images before (green; left) and after (red; center) gutta-percha and sealer removal. The right image depicts the superimposition. The evaluation was performed over an 11 mm canal segment from the canal orifice to 3 mm from the apex. The removal rate was calculated using the following formula: [pre-removal gutta-percha and sealer volume − post-removal gutta-percha and sealer volume]/pre-removal gutta-percha and sealer volume) × 100.

2.4. Automated Root Canal Instrumentation Device with Controlled Downward Loading

Gutta-percha and sealer removal was performed using the automated root canal instrumentation system with integrated torque and force measurement, as described in our previous studies [16,17], where the system was employed exclusively for the evaluation of root canal shaping. Briefly, the instrumentation setup consisted of a modified Tri-Auto ZX motor (J. Morita) mounted on a motor-driven testing stand (MX2-500N; Imada, Aichi, Japan). The specimens were secured in a rigid holder linked to the torque/force sensing system. The handpiece was held on the stand via an electromagnet and balanced with counterweights on pulleys. When the electromagnet was deactivated, it allowed the handpiece to drop under a preset load of 2, 3, or 4 N. The torque/force sensing system consisted of strain gauges (KFG-2-120-D31-11; Kyowa, Tokyo, Japan) and a load cell (LUX-B-ID; Kyowa), respectively. The signals were amplified with a PCD-400A amplifier (Kyowa) and captured using DCS-100A data acquisition software (version 4.31; Kyowa).

2.5. Root Canal Filling Removal

Two rotational speeds (400 and 800 rpm) were chosen to represent the lower and upper limits of the manufacturer-recommended operating range for the HyFlex Remover instrument. The downward loads (2, 3, and 4 N) were determined based on preliminary experiments, with reference to the load range reported in a previous study [16].

The coronal 3 mm of gutta-percha was initially removed using a HyFlex EDM Orifice Opener (#25/0.12; Coltene/Whaledent), and each canal was mounted on the automated root canal instrumentation device. The HyFlex Remover instrument was set with its tip positioned 3 mm below the orifice. A constant load of 2 N, 3 N, or 4 N was applied during rotation (low-speed group: 400 rpm; high-speed group: 800 rpm; torque: 2.5 N·cm, according to the manufacturer's recommendation). Removal was terminated when the file reached 3 mm short of the apex by following the manufacturer's recommendation to prevent unnecessary apical enlargement and reduce the risk of file fracture [7]. A new micro-CT scan was performed with the same parameters as described previously.

2.6. Evaluation

The specimens were arbitrarily assigned to six experimental groups according to two rotational speeds (400 and 800 rpm) and three force conditions (2, 3, and 4 N), resulting in six combinations (n = 10/group). Torque and force generated within the canal were measured in real-time using the torque/force analyzing unit of the instrumentation device, and maximum force and torque were recorded. Torque data were collected every 0.01 s, and cumulative torque was calculated as the sum of values exceeding 0.1 N·mm. The time required for the instrumentation was measured. Gutta-percha extrusion was recorded. Micro-CT scans before and after removal were used to measure the remaining gutta-percha volume from the canal orifice to 3 mm short of the apex, using the Amira 3D 2023.2 software, and the removal rate (%) was calculated as shown in Figure 2.

2.7. Statistical Analysis

Data were analyzed using IBM SPSS Statistics 27 (IBM Corp., Armonk, NY, USA). Normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene's test for all outcome variables. The maximum torque, cumulative torque, maximum force, removal time, and removal rate were analyzed using a two-way fixed-effects analysis of variance (ANOVA), with downward load and rotational speed as independent factors. When significant effects were detected, post hoc comparisons were performed using the Bonferroni correction (α = 0.05).

3. Results

3.1. Removal Efficiency (Removal Rate and Time)

The removal rate was significantly higher in all 400 rpm groups than the corresponding 800 rpm groups under the same load conditions ($p < 0.001$; Figure 3A). However, no significant differences were observed between the different load groups at the same rotational speed ($p > 0.05$).

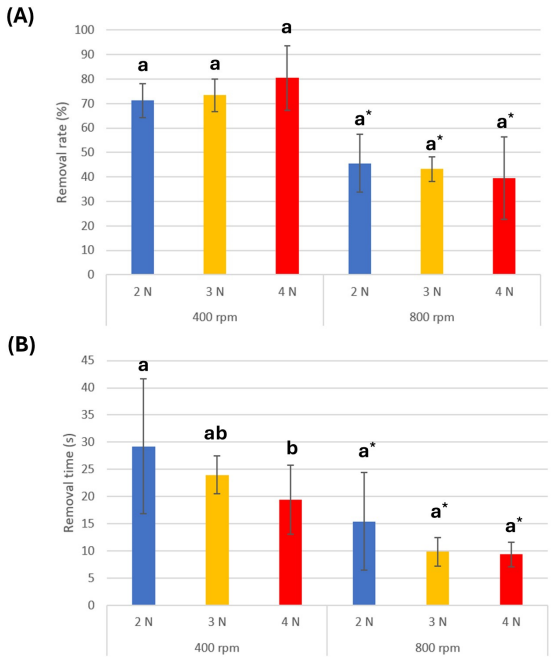


Figure 3. Removal rate (**A**) and removal time (**B**) of gutta-percha and AH Plus sealer using the HyFlex Remover instrument under varying vertical loads and rotational speeds. Values are presented as the mean ± standard deviation (n = 10). Different lowercase letters denote significant differences between load conditions at each rotational speed, whereas an asterisk (*) denotes a significant difference between rotational speeds at each load condition.

The removal time was consistently longer in all 400 rpm groups than in the corresponding 800 rpm groups ($p < 0.001$; Figure 3B). In the 400 rpm condition, the 400-2 N group required a significantly longer removal time than the 400-4 N group ($p = 0.009$; Figure 3B). No file fracture, ledging, or gutta-percha extrusion occurred during the removal procedures.

3.2. Torque Characteristics

The 800-2 N group showed significantly lower maximum torque than the 800-4 N groups ($p = 0.006$; Figure 4A), with no significant differences between the 400 rpm groups or across different rotational speeds (all $p > 0.05$).

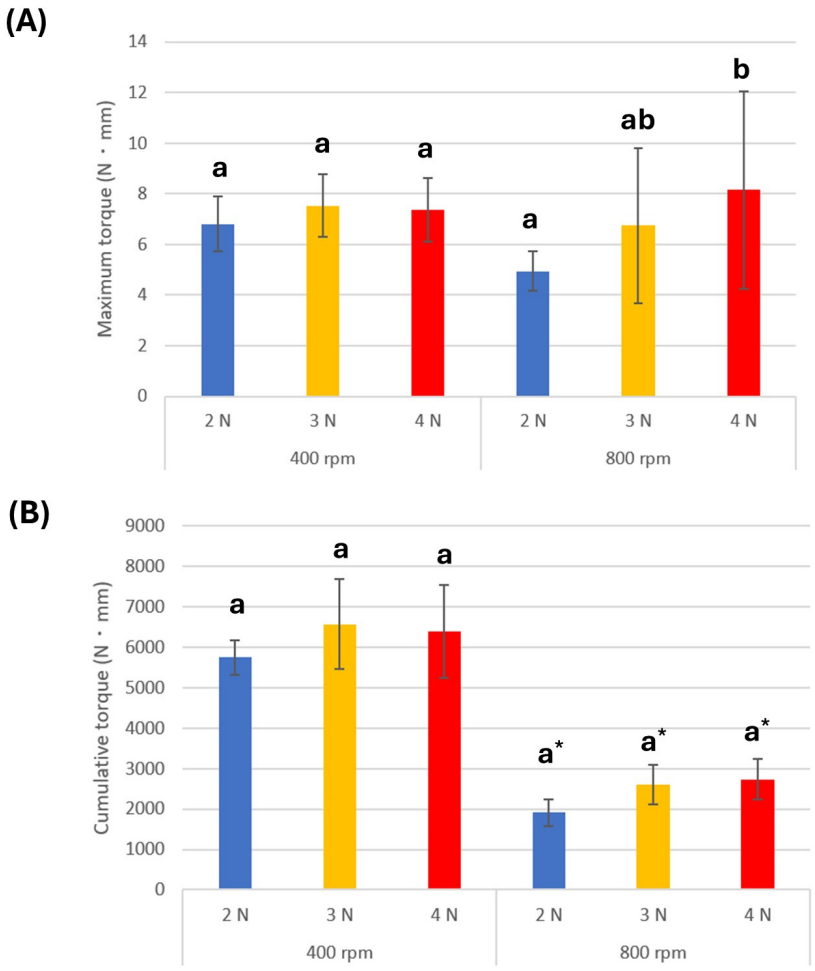


Figure 4. Maximum torque (**A**) and cumulative torque (**B**) generated during the removal of gutta-percha and AH Plus sealer using the HyFlex Remover instrument under varying vertical loads and rotational speeds. Values are presented as the mean ± standard deviation ($n = 10$). Different lowercase letters denote significant differences between load conditions at each rotational speed, whereas an asterisk (*) denotes a significant difference between rotational speeds at each load condition.

Cumulative torque was significantly higher in all 400 rpm groups than the corresponding 800 rpm groups under the same load conditions (all $p < 0.001$; Figure 4B).

3.3. Maximum Force

The maximum force increased with the applied load, with significant differences between the 400-2 N, 400-3 N, and 400-4 N groups, as well as between the 800-2 N, 800-3 N, and 800-4 N groups (all $p < 0.001$; Figure 5). At 3 N and 4 N, the 400-3 N and 400-4 N groups showed significantly lower maximum force values than the 800-3 N and 800-4 N groups, respectively ($p = 0.039$ and $p < 0.001$, respectively; Figure 5).

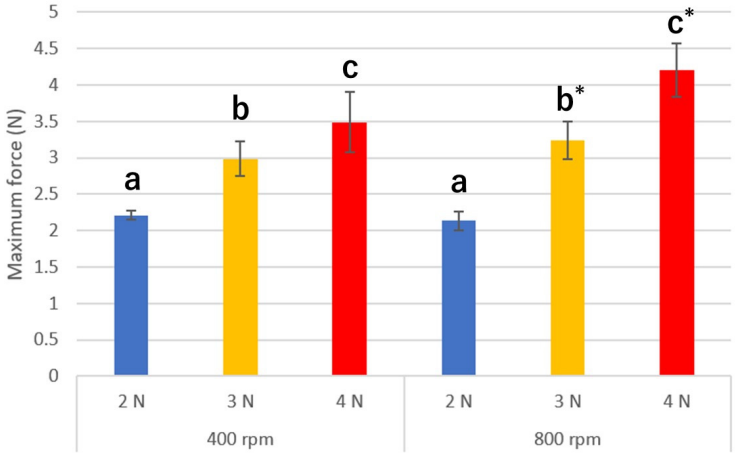


Figure 5. Maximum force generated during the removal of gutta-percha and AH Plus sealer using the HyFlex Remover instrument under varying vertical loads and rotational speeds. Values are presented as the mean ± standard deviation (n = 10). Different lowercase letters denote significant differences between load conditions at each rotational speed, whereas an asterisk (*) denotes a significant difference between rotational speeds at each load condition.

4. Discussion

To the best of our knowledge, this is the first study to evaluate the effects of different downward loads, in combination with rotational speeds, on the efficiency and torque/force generation of gutta-percha/sealer removal with an NiTi rotary instrument. Under the present experimental conditions, the downward load and rotational speed influenced the removal performance of the HyFlex Remover instrument. The maximum force significantly increased with increasing downward load, while cumulative torque and removal rate were significantly greater at 400 rpm than with 800 rpm, with longer removal times particularly under lower loads. Therefore, the null hypothesis was rejected. These findings indicate that downward loads and rotational speeds directly affect the removal efficiency and mechanical stress applied to the instrument and the canal wall.

In this study, the HyFlex Remover was selected as a representative contemporary heat-treated NiTi rotary removal instrument. Previous studies have reported that its removal performance is comparable to or, under certain experimental conditions, greater than that of other NiTi retreatment systems, with reports of reduced residual gutta-percha, shorter instrumentation time, and higher patency rates [8–10]. The instrument features a triple-helix blade design, a relatively large taper and core diameter, and is manufactured from CM-wire [8], which predominantly exhibits a martensitic structure at room temperature and transitions to a stiffer mixed martensitic–austenitic phase at body temperature [25]. These metallurgical and geometric characteristics have been linked with increased cyclic fatigue resistance compared with conventional NiTi instruments [26], along with high buckling resistance [8], which may facilitate penetration into gutta-percha and contribute to effective filling material removal. Nevertheless, previous micro-CT and CLSM studies have consistently demonstrated that complete elimination of root canal filling materials cannot be achieved with any currently available NiTi retreatment system [4,6,8–10,24], and the results of the present study further support these observations.

Proper manipulation of NiTi rotary instruments, particularly precise control of downward load, is essential for safe and effective clinical performance [27]. Excessive apical force has been reported to promote instrument engagement with the canal wall, resulting in increased torsional stress and a higher risk of instrument fracture [28]. However, standardized evidence regarding the influence of downward load remains limited because this parameter is difficult to isolate under experimental conditions. Using an automated instrumentation

system comparable to that employed in the present study, our previous investigations demonstrated that increased downward load led to significantly higher screw-in forces during canal shaping procedures [16], an effect that was mitigated when heat-treated NiTi instruments were used [17]. In addition to downward load, pecking amplitude—the magnitude of the instrument's vertical in-and-out motion—has been shown to influence axial loading, with larger amplitudes increasing screw-in force and improving canal centering ability [29,30]. However, their effect on cyclic fatigue resistance appears to be instrument-dependent [30–32]. Despite these findings, the impact of downward load on the efficiency of gutta-percha and sealer removal, as well as on torque and force generation during retreatment procedures, has not yet been clarified. The present study addresses this gap by evaluating the effects of controlled downward load under standardized conditions.

Under the conditions of this experiment, maximum force significantly increased with increasing applied load, and maximum torque also significantly increased at 4 N, while the removal time was significantly longer at 2 N. Applying a larger load allows the NiTi rotary instrument to engage gutta-percha more aggressively, improving cutting efficiency and reducing the removal time. However, the increased contact resistance between the instrument and material may raise the mechanical load on the instrument, resulting in higher torque during cutting. Based on our finding that the removal rate did not vary with the applied load, 2 N and 3 N loads appear to be the most appropriate under the conditions of this study because they shortened the removal time while preventing excessive torque generation.

Rotational speed is another factor that affects the shaping behavior of NiTi instruments, although its effects remain controversial. Higher rotational speeds have been associated with shorter working times during root canal filling removal, likely due to enhanced cutting efficiency [20,21]. However, increased rotational speed has also been linked to a higher incidence of instrument fracture [33], potentially due to elevated stress caused by an increased strain rate and reduced time for stress relaxation and crystalline transformation. In contrast, some studies have reported that higher speeds can generate lower torque and apical force, likely because faster cutting reduces the contact time and contact area, and does not necessarily increase the fracture risk [34–36]. These conflicting findings indicate that the influence of rotational speed is highly dependent on the experimental context, instrument design, and evaluated outcome variables, highlighting the need for controlled investigations focusing on specific clinical procedures such as gutta-percha removal.

The differences in torque generation and the removal rate between different rotational speed in this study may be attributed to variations in the cutting dynamics and instrument–material interaction [7,34]. In this study, the removal rate and cumulative torque were higher and the removal time was longer in the 400 rpm group than in the 800 rpm group, regardless of the applied load. A possible explanation is that a lower rotational speed may prolong the contact time and friction with gutta-percha, and thereby raising cumulative torque and improving removal efficacy. However, direct experimental verification (e.g., friction coefficient measurement, real-time torque profiling) is required to confirm this assumption. In contrast, at a higher rotational speed, the contact time per revolution may be shorter, which contributes to faster material removal, but may slightly reduce cutting efficiency. Additionally, a higher rotational speed may increase frictional heat [37], softening gutta-percha for faster removal, but also may make the NiTi alloy more austenitic, reducing fatigue resistance [11]. Under the present experimental conditions, while a rotational speed of 400 rpm increased removal efficacy, it was associated with longer working time and greater cumulative torque, which may increase the risk of torsional stress on the instrument. From a clinical perspective, a higher rotational speed such as 800 rpm may therefore offer practical advantages by reducing procedure time and limiting torque accumulation during retreatment. Nevertheless, the present findings also suggest that an intermediate

rotational speed could potentially provide a more balanced trade-off between efficiency and mechanical safety, although further investigation is required.

Taken together, the present study provides novel insight by demonstrating how controlled downward load and rotational speed interact to influence both removal efficiency and mechanical stress during gutta-percha and sealer removal, an aspect that has not been addressed in previous retreatment studies.

Study Limitations

While informative on gutta-percha/sealer removal using NiTi rotary files, this study is not without limitations. Simulated straight resin root canal blocks were used to improve experimental reproducibility by standardizing canal wall hardness and morphology; however, their physical properties, particularly hardness, differ from those of natural dentin [38]. Furthermore, given the high prevalence of curved root canals (84%) [39], the inclusion of curved canals, especially from anatomically matched human teeth [40], would enhance clinical relevance. In addition, only one NiTi instrument system was evaluated, limiting the generalizability of the findings. It remains unclear whether the observed effects are specific to the system's design and metallurgy or applicable to other systems. Future studies should therefore incorporate multiple instrument systems, canal curvatures, and clinically relevant conditions to identify optimal mechanical parameters for effective and safe gutta-percha removal.

5. Conclusions

This study assessed how downward load and rotational speed affect gutta-percha and sealer removal efficiency and torque/force of a NiTi rotary instrument in simulated straight resin canals. Under the present experimental conditions, lower downward loads reduced torque but prolonged the working time, whereas higher rotational speeds shortened both the working time and torque, albeit with a lower removal rate. These findings indicate that both load and speed parameters affect the efficiency and safety of gutta-percha and sealer removal, and that optimizing these factors could improve outcomes in clinical practice. A combination of a lower load and a higher rotational speed appeared advantageous for balancing overall performance.

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Conflicts of Interest: The authors declare no conflicts of interest.

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