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Mechanical behavior of dental training teeth and bovine dentin under motion-controlled dynamic cutting: A study using three-axis load measurement and SEM analysis

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Mechanical behavior of dental training teeth and bovine dentin under motion-controlled dynamic cutting: A study using three-axis load measurement

Advisor Shin, Yooseok

A Master's Thesis Submitted
to the Department of Dentistry
and the Committee on Graduate School
of Yonsei University in Partial Fulfillment of the
Requirements for the Degree of
Master of Dental Science

Hwang, Ju-yeon

June 2025

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2025 년 5 월

황주연 올림

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Abstract

Mechanical behavior of
dental training teeth and bovine dentin
under motion-controlled dynamic cutting:
A study using three-axis load measurement and SEM analysis

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(Directed by Professor Yooseok Shin, DDS, MSD, PhD)

Dental training teeth are widely used in preclinical education for practicing tooth preparation. These training teeth are manufactured from synthetic resins, which differ from natural teeth in terms of composition and mechanical properties. Although dental training teeth are commonly employed in educational settings many prior studies have examined only uniaxial cutting forces or conducted qualitative assessments, which may not adequately represent the mechanical complexity of clinical procedures. To address these limitations, this study aimed to quantitatively evaluate the cutting force characteristics of dental training teeth and bovine dentin using a custom-built three-axis force measurement system under simulated cavity preparation movements.

A computer-controlled dynamic cutting system with a three-axis load cell was used to measure cutting forces during cutting movements: vertical-downward (1.5 mm), horizontal (6 mm), and vertical-upward (1.5mm), all performed at a feed rate of 1 mm/s with a bur rotational speed of 200,000 rpm (revolutions per minute). After cutting, scanning electron microscopy (SEM) was used to examine surface characteristics of the samples and the cutting burs.

Statistical analysis was performed using one-way ANOVA followed by post hoc

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Tukey's test. In vertical-downward movement, Nissin and Frasaco exhibited higher Fr values than bovine dentin ($p < 0.001$), with no significant difference between the two ($p = 0.714$). During horizontal movement, all training teeth demonstrated significantly higher Fr values than bovine dentin ($p < 0.001$), and pairwise comparisons among the training teeth also showed significant differences ($p < 0.05$). In vertical-upward movement, Frasaco and Genoss showed significantly higher Fr values than bovine dentin ($p < 0.001$), while no significant difference was observed between Nissin and Frasaco ($p = 0.529$). These results suggest that bovine dentin exhibited lower cutting resistance than dental training teeth across all tested movement directions.

SEM analysis of carbide burs (×100 and ×300) revealed fine chipping and surface wear on the cutting edges after cutting Frasaco and Nissin, whereas no comparable wear was observed on burs used for bovine dentin. SEM analysis of the cut surfaces (×500 and ×1,500) revealed that dental training teeth exhibited micro-cracks, fractures, and debris accumulation, whereas bovine dentin demonstrated smoother surfaces with fewer defects and minimal debris.

This study identified differences in mechanical behavior between dental training teeth and bovine dentin under motion-controlled dynamic cutting, as demonstrated by three-axis force measurements and SEM analysis. While dental training teeth exhibited higher cutting resistance and distinct surface damage, bovine dentin showed lower resistance and smoother features. This study provided quantitative evidence of mechanical differences between dental training teeth and bovine dentin under simulated dynamic cutting. These differences, confirmed through force measurements and SEM analysis, underscore the need for educators and students to acknowledge such material-specific responses during training. Rather than assuming equivalence with natural tissue, training exercises should be designed and approached with an understanding of these limitations, so that learners develop appropriate expectations and techniques in preparation for clinical practice.

Keywords: Bovine dentin, Cutting force, Dental training teeth, High-speed handpiece, Scanning Electron Microscopy (SEM), Three-axis load cell

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1. Introduction

In preclinical dental education, students acquire technical competence through repeated tooth preparation exercises using commercial dental training teeth (Cresswell-Boyes, 2021). These training teeth serve as practical alternatives to extracted human teeth by addressing ethical concerns and reducing variability associated with anatomical differences and limited availability. Due to their consistent anatomical form, uniform material properties, and compatibility with typodont systems, they are widely used in prosthodontic and restorative training. This enables students to perform essential procedures—such as tooth preparation, cavity restoration, and endodontic access—under reproducible conditions, while also allowing for objective assessment of technical proficiency (Decurcio et al., 2019; Frazier & Dlugokinski, 1999). Although dental training teeth mimic the external form of natural teeth, dental training teeth do not fully replicate the tactile sensation encountered during cutting, primarily due to differences in material properties (Cresswell-Boyes et al., 2022).

Previous studies have reported that discrepancies in cutting force and resistance between dental training and natural teeth can affect the operator's perception of force and hand control during cavity preparation (Cresswell-Boyes et al., 2025; Elias et al., 2003). Given that such procedures involve the irreversible removal of tooth structure can impact the clinical outcome, potentially resulting in excessive reduction, compromised margins, or unintended pulp exposure. These concerns underscore the importance of using training models that closely simulate the mechanical and tactile properties of natural teeth (Soriano et al., 2013; Tanaka et al., 1993).

Most commercial dental training teeth are composed of melamine resin, a thermosetting polymer synthesized through the polymerization of melamine and formaldehyde (Behr et al., 2011). This composition supports their durability in repetitive preclinical training environments. However, their mechanical properties—such as hardness,

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elastic modulus, and fracture toughness—differ from those of natural teeth, which can influence cutting behavior and resistance during operative procedures (Cresswell-Boyes et al., 2022). Although some manufacturers have attempted to enhance the realism of dental training teeth by incorporating layered structures or simulating the dentin–enamel junction (DEJ), the mechanical behavior of the natural enamel–dentin complex has not yet been fully reproduced. Previous studies using 3D-printed typodont teeth with reinforced composite resins based on micro-CT data showed improved material design but still demonstrated significant differences in cutting behavior compared to natural teeth (Cresswell-Boyes, 2021; Cresswell-Boyes et al., 2022).

Previous studies evaluating dental training teeth have often utilized single-axis load measurements conducted under controlled laboratory conditions (Siegel & Fraunhofer, 1997). However, during clinical tooth preparation, high-speed handpieces generate forces in multiple directions due to varied hand movements. As a result, single-axis analysis may not fully reflect the dynamic and multidirectional nature of cutting interactions (Funkenbusch et al., 2015; Tanaka et al., 1993). In addition, many existing studies rely on subjective assessments, which can vary depending on operator skill and experience, potentially limiting consistency in material comparisons (Lee et al., 2022). These methodological differences suggest the need for a more comprehensive and objective approach that captures the full range of force components involved in clinical tooth preparation.

Bovine teeth have a high similarity in chemical composition and physical properties to human teeth, making them a useful substitute in dental materials research (Reis et al., 2004; Teruel Jde et al., 2015). Compared to human teeth, bovine teeth have the advantage of allowing researchers to control variables such as age, diet, size, and color, thereby minimizing experimental bias (Franchini Pan Martinez et al., 2023). A meta-analysis conducted by Soares further supports their reliability as a substitute for human teeth, confirming their comparable structural and material properties, including enamel and dentin composition (Soares et al., 2016). Additionally, some studies suggest that their mechanical properties, such as hardness

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and wear resistance, resemble those of human teeth, potentially providing a similar cutting sensation in experimental conditions (Yassen et al., 2011).

This study aimed to quantitatively evaluate the mechanical behavior of dental training teeth and bovine dentin under simulated cutting conditions. Cutting forces were measured along three axes using a three-axis load cell during simulated cutting in three movement directions—vertical-downward, horizontal, and vertical-upward—and were compared.

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2. Materials and Methods

Figure 1 illustrates the research workflow, focusing on the comparison of cutting force among the three dental training teeth and bovine dentin.

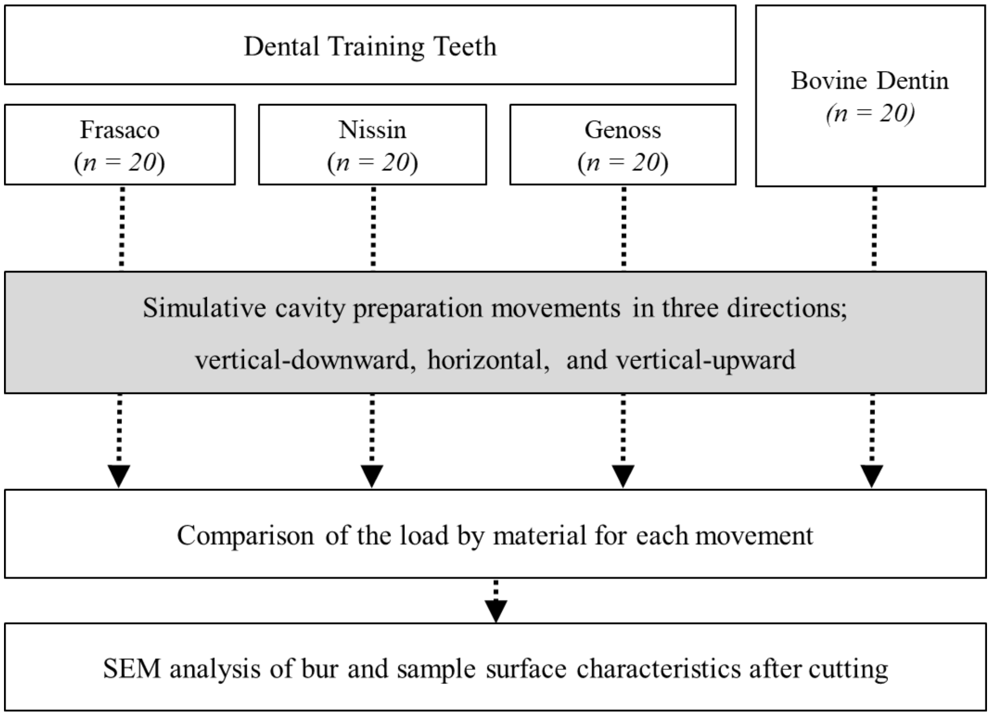

Figure 1. Overall workflow of the research.

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2.1. Sample Size Determination

To analyze the three-axis load exerted on three types of dental training teeth and bovine dentin using a high-speed handpiece, G*Power (Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany) software was used to calculate the sample size. G*Power is a widely used tool for estimating the appropriate sample sizes in research designs (Faul et al., 2009; Kang, 2021). In this study, one-way ANOVA was employed to calculate the sample size for comparing the mean differences between multiple groups.

The main statistical parameters for sample size calculation were as follows:

1. **Significance level (α):** Set to 0.05 to limit the probability of a Type I error (i.e., concluding there is a difference when there is actually none) to 5%.

2. **Power (1-β):** Set to 0.80, ensuring an 80% chance of detecting a real difference if it exists.

3. **Effect size:** Based on previous literature and pilot testing, the effect size for the comparison between dental training teeth and bovine dentin was estimated to be large (Cohen's f = 0.4), and this value was used in the analysis. An effect size of Cohen's f = 0.4 indicates a substantial difference between the groups, making it appropriate for the experimental design.

Based on these statistical parameters, G*Power software was used to calculate the sample size for each group using one-way ANOVA. The results showed that a minimum of 19 samples were required for each group. Since this study compared four groups (three dental training teeth and bovine dentin group), 20 samples were set for each group to enhance statistical reliability.

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2.2. Production of the test samples

In this study, a total of four material groups were analyzed, comprising three commercial dental training teeth and one bovine dentin group. The types and compositional characteristics of these groups are summarized (Table 1). Each sample consisted of two main parts: a bottom and a body. The bottom part was a flat square with four holes at each corner, allowing it to be securely fastened to the three-axis load cell with screws. This ensured that the sample and the three-axis load cell remained attached to the device during dynamic cutting and measurement processes. The body part was fabricated in a uniform size of 20 mm in height across all groups to ensure consistent cutting conditions (Fig. 2).

Three types of dental training teeth were used in this study: Frasaco (frasaco GmbH, Tettnang, Germany), Nissin (Nissin Dental Products Inc., Kyoto, Japan), and Genoss (GENOSS, Suwon, Korea). Genoss provided a product currently under Research and Development (R&D) for preliminary evaluation. Dental training teeth were fabricated using the mandibular left first molar, as it provides broad occlusal surface. To ensure uniformity among all samples, the cusps of each tooth were leveled and polished. The bottom parts were designed using CAD software (Rhino 7, Robert McNeel & Associates, Seattle, USA). For fabrication, a 3D printing resin (Model; Formlabs, Somerville, USA) and a 3D printer (Form 3+; Formlabs) were employed. Following the manufacturer's guidelines, the printed resin components were post-cured for the specified cleaning and curing durations. Finally, the body and bottom parts were adhered securely with an instant adhesive (Loctite 401; Loctite, Düsseldorf, Germany) (Fig. 2A-C).

Bovine teeth were collected and processed to prepare test samples for this study. Twenty fresh, caries-free bovine incisors were obtained from a certified livestock processing plant (Seoul, South Korea). After washing the teeth with water to remove blood, they were stored in distilled water. For the preparation of bovine teeth samples, the root portion of the tooth was removed according to the research purpose, leaving only the crown portion. Additionally, bovine dentin samples were prepared to obtain data from the dentin layer. The dentin layer was selected as the measurement layer due to its processability, thickness, and consistent response under in vitro conditions, allowing for reliable and reproducible cutting force analysis. The samples were then precisely trimmed and polished along the mesiodistal (M-D) direction using a model trimmer equipped with a diamond wheel (Y-230, Yoshida Dental Mfg. Co., Ltd, Tokyo, Japan). During this process, surface defects were carefully minimized to maintain the integrity of the prepared layer. The test samples were prepared by fixing and attaching them to bottom parts using self-curing resin (PATTERN RESIN™ LS, GC America Inc, America) and instant adhesive (Loctite 401; Loctite, Düsseldorf, Germany). The prepared test samples were maintained in distilled water at room temperature to prevent dehydration and preserve their mechanical and structural stability, minimizing alterations caused by environmental exposure (Fig. 2D).

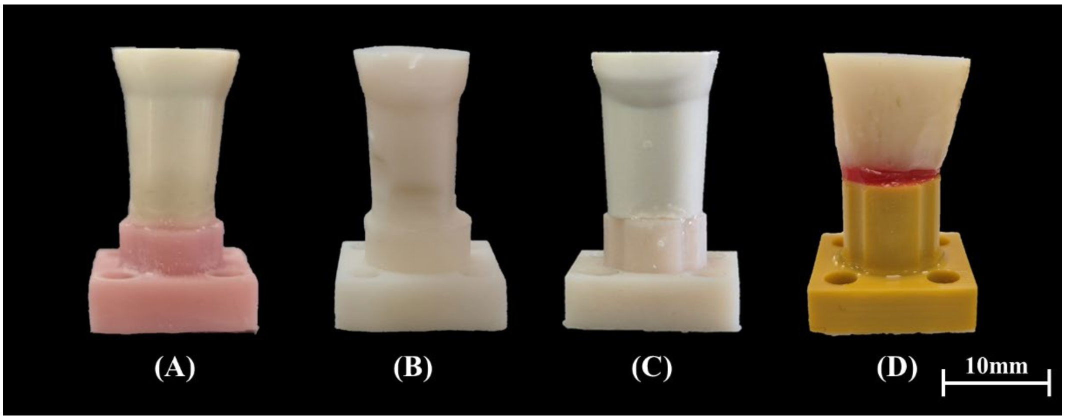

Figure 2. Image of the test sample. **(**A) Frasaco, (B) Nissin, (C) Genoss, (D) Bovine dentin.

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Table 1. Types and Compositions of groups tested.

Classification	Product Name	Manufacturer	Composition (wt.%)
Dental training teeth	Frasaco	frasaco GmbH, Tettnang, Germany	Thermosetting melamine resin compound[a]
	Nissin	Nissin Dental Products Inc., Kyoto, Japan	
	Genoss	GENOSS, Suwon, Korea	60-70% Melamine-formaldehyde condensate 20-30% Cellulose <5% Barium sulfate <1% Titanium dioxide <0.3% Phthalic anhydride 10% Melamine 0.5% Formaldehyde
Human teeth	Enamel		Inorganic 91.4% Hydroxyapatite (Ca, P, O, CO_3^{2-}) Organic 5.7% Water 2% Trace Elements <1% Cl, Cu, Zn, Sr, Mg, Fe, F, Mn
	Dentin		Inorganic 71.2% Hydroxyapatite Organic 20% Type I collagen Water 6.5% Trace Elements <1% Zn, Sr, Mg, Cu, Fe, F, K, Na
Bovine teeth	Enamel		Inorganic 81.4% Hydroxyapatite (Ca, P, O, CO_3^{2-}) Organic 10.9% Water 4.6% Trace Elements <1% Na, Mg, Cl, K, Sr, Zn, Cu, Fe, Mn, F
	Dentin[b]		Inorganic 70.2% Hydroxyapatite Organic 19.2% Type I collagen Water 8.2% Trace Elements <1% Zn, Sr, Mg, Cu, Fe, F, K, Na

[a] Detailed composition was not disclosed by the manufacturer due to proprietary restrictions.

[b] In this study, only the dentin layer of the tooth was used (Teruel Jde et al., 2015).

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2.3. Experimental equipment

Dynamic cutting tests were conducted using a computer-controlled system (Cresswell-Boyes, 2021). The system consisted of two primary components (Fig. 3):

1. Dynamic cutting with motion control
2. Three-axis load measurement

These components were integrated into a computerized motion control system, ensuring high precision and repeatability in the cutting process (Lee et al., 2024). A detailed description of the motion control system and force measurement setup is provided in the following sections.

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2.3.1. Dynamic cutting with motion control

A dental high-speed handpiece (Ti-Max Z95L, NSK Dental, Tokyo, Japan) equipped with a pear-shaped tungsten carbide bur (diameter: 0.8 mm, FG330, Komet, Lemgo, Germany) was utilized in this study. The handpiece was connected to a compact electric micromotor (NLX nano S120E, NSK Dental) and securely mounted on a vertical stage (L-836.501200, Physik Instrumente GmbH, Germany), positioned parallel to the mounting platform. This vertical stage was then fixed onto a horizontal stage of the same model (L-836.501200, Physik Instrumente GmbH) (Fig. 3A). The movements of both stages were precisely controlled by a motor controller (C-663.12; Physik Instrumente GmbH). To ensure accurate performance, calibration tests were conducted for each bur before the cutting tests.

Initially, the rotating bur was positioned 10 mm away from the sample along the Z-axis and moved toward it at a feed rate of 1 mm/s. Sufficient time was allowed for the bur to reach its full rotational speed of 200,000 rpm (revolutions per minute) before making contact with the sample surface. The feed rate and rotational speed were kept constant from the beginning to the end of each cutting procedure. A new carbide bur was used for each trial, and the cooling water flow rate from the handpiece’s four-hole spray system was kept constant at 50 mL/min to prevent overheating.

The cutting experiment followed a structured sequence of movements. The bur first performed a vertical downward movement of 1.5 mm, followed by a horizontal movement of 6 mm, and then a vertical upward movement of 1.5 mm, forming a simple linear path that mimics the motion used during cavity preparations (Fig. 3B). A brief pause of 1 second was applied at two transition points: (1) from the vertical-downward movement to the horizontal movement, and (2) from the horizontal movement to the vertical-upward movement. After completing the sequence, the bur returned to its initial position.

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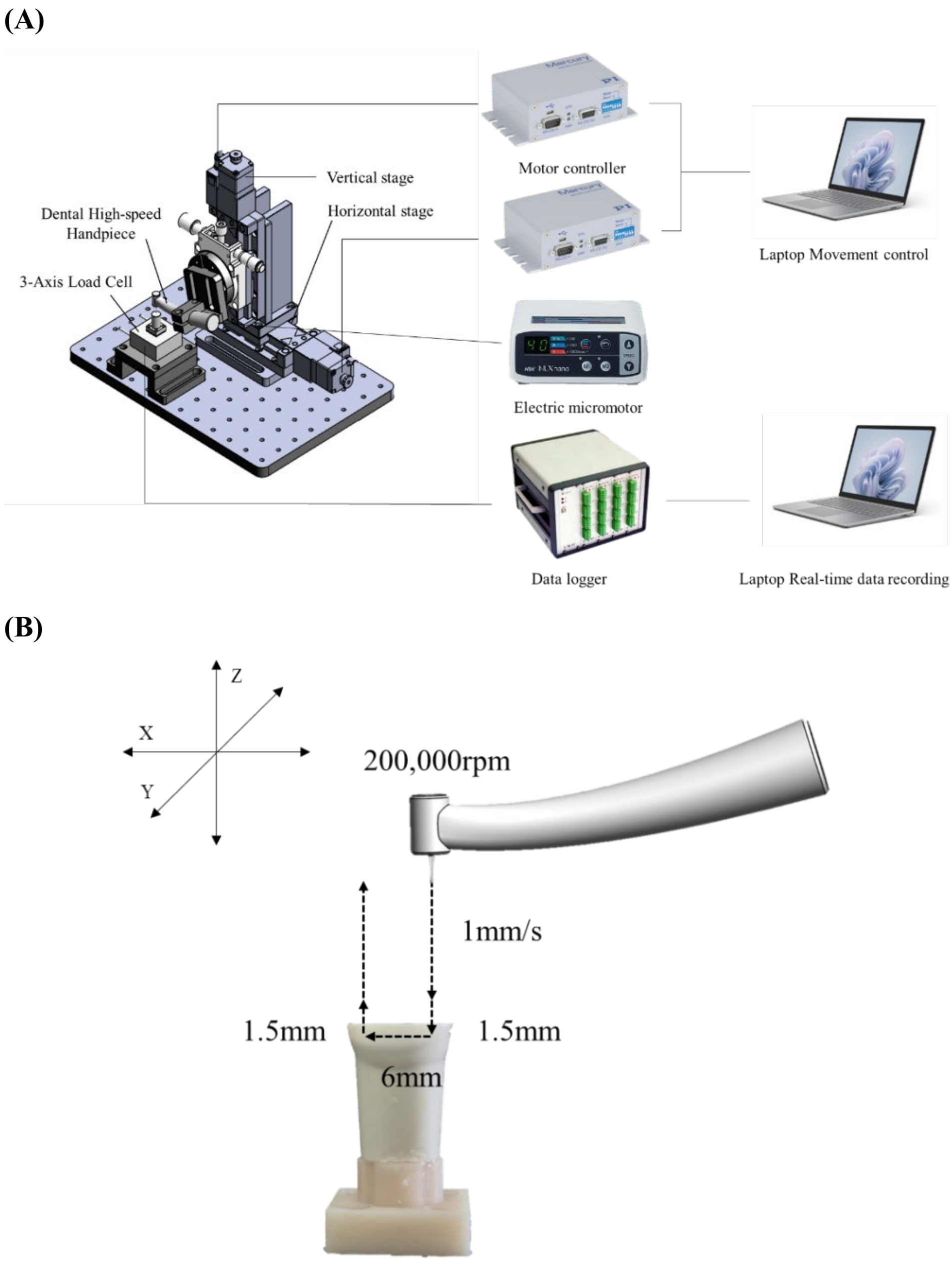

Figure 3. Schematic diagram illustrating the experimental setup and dynamic cutting movements. (A) Experimental setup for dynamic cutting, incorporating motion control and load measurement (B) Computer-controlled movements of the dental high-speed handpiece.

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2.3.2. Three-axis load measurement

The test samples were securely mounted onto a three-axis load cell (ZMAS-50N, CAS, Yangju, Korea) using four screws to ensure stable fixation. The screws were evenly tightened by hand until no further manual tightening was possible, without applying excessive force that could affect measurement accuracy or exceed the load cell's capacity of 50N. All Force data were continuously recorded along the X-, Y-, and Z-axes at a sampling rate of 10 Hz using a three-axis load cell and continuously stored using a data logger (GTDL-350, CAS) connected to a data acquisition system.

In this study, these components are collectively described as cutting forces to reflect their role in representing material-specific resistance during dynamic cutting. The X-axis is the direction of the bur's movement during the horizontal cutting process. Fx (force along the X-axis) indicates the cutting force that opposes this horizontal motion. The Y-axis is mutually perpendicular to the X-axis and lies within the XY-plane. Fy (force along the Y-axis) indicates the lateral force acting perpendicular to the cutting direction, which may be influenced by tool deviation or side forces. The Z-axis is normal to the XY-plane and defines the vertical direction in the three-dimensional coordinate system. Fz (force along the Z-axis) indicates the force that opposes vertical cutting movements, such as when the bur moves downward into the material or moves upward.

The three-axis load cell measured directional reaction forces (Fx, Fy, Fz; unit: N), corresponding to the instantaneous mechanical resistance of the material during rotary instrumentation.

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2.4. Scanning electron microscopy analysis

After the dynamic cutting process for each material group, scanning electron microscopy (SEM; Hitachi S-3000N, Hitachi, Japan) was used to analyze bur surface wear and the characteristics of the cut surfaces of the sample.

Bur surfaces were examined at ×100 and ×300 magnifications to assess wear patterns and debris accumulation. Cut sample surfaces were observed at ×500 and ×1,500 magnifications to evaluate surface roughness, micro-cracks, fractures, residual debris distribution, and cutting-induced alterations under different cutting orientations.

The sample surfaces were examined under three distinct conditions: (1) prior to cutting after surface polishing, (2) after cutting without debris removal, and (3) after ultrasonic cleaning to remove debris. For conditions (2) and (3), specific regions that underwent vertical-downward and horizontal cutting motions were examined using SEM.

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2.5. Statistical analysis

The median value of the recorded forces was selected as the representative measure when comparing the forces along the X-, Y-, and Z-axes, as well as the resultant load during vertical-downward, horizontal, and vertical-upward movements. To better reflect the multidirectional force encountered during dynamic cutting, the resultant force (Fr), calculated as the vector sum of the X-, Y-, and Z-axis components, was analyzed in addition to individual axis forces. Statistical analysis was conducted using one-way analysis of variance (ANOVA) to identify significant differences among the measurement groups. Post hoc analyses were conducted using Tukey's test to identify significant pairwise differences. All statistical analyses were carried out using SPSS version 27 (SPSS Inc., Chicago, Illinois, USA), with the significance level set at $\alpha = 0.05$.

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3. Results

3.1. Patterns of the real-time 3-axis load

The cutting forces of Frasaco, Nissin, Genoss, and bovine dentin were analyzed across three movement directions—vertical-downward, horizontal, and vertical-upward—to investigate their mechanical responses during dynamic cutting. The force patterns observed along the X and Y axes exhibited similar trends across all movement directions, though with variations in magnitude. In contrast, the Z-axis showed a distinct pattern, indicating different cutting forces (Fig 4).

The X- and Y-axes direction force graphs demonstrated relatively low cutting forces during vertical downward movement. During horizontal movement, Nissin exhibited the greatest force magnitude throughout the movement, whereas Frasaco and Genoss exhibited intermediate levels, and bovine dentin demonstrated the lowest force response. In the X-axis direction force graph, Nissin exhibited gradually increasing forces during the horizontal cutting phase, which differed from the patterns observed in the other groups. In contrast, in the Y-axis direction force graph, Nissin showed a relatively flat force like those of other groups. In the vertical upward movement, the cutting forces on both axes decreased significantly for all groups (Fig 4 A-B).

The Z-axis direction force graphs showed variation depending on the material and movement. The highest Z-axis cutting forces were observed during vertical downward movement for Frasaco and Nissin. During horizontal movement, the Z-axis cutting force gradually increased for Frasaco and Nissin, whereas Genoss and bovine dentin exhibited lower loads and appeared to maintain a consistent cutting force. In the vertical upward phase, the Z-axis cutting forces consistently decreased across all groups (Fig. 4C).

Overall, These results reveal the differences in the mechanical responses of the tested groups when subjected to dynamic cutting conditions.

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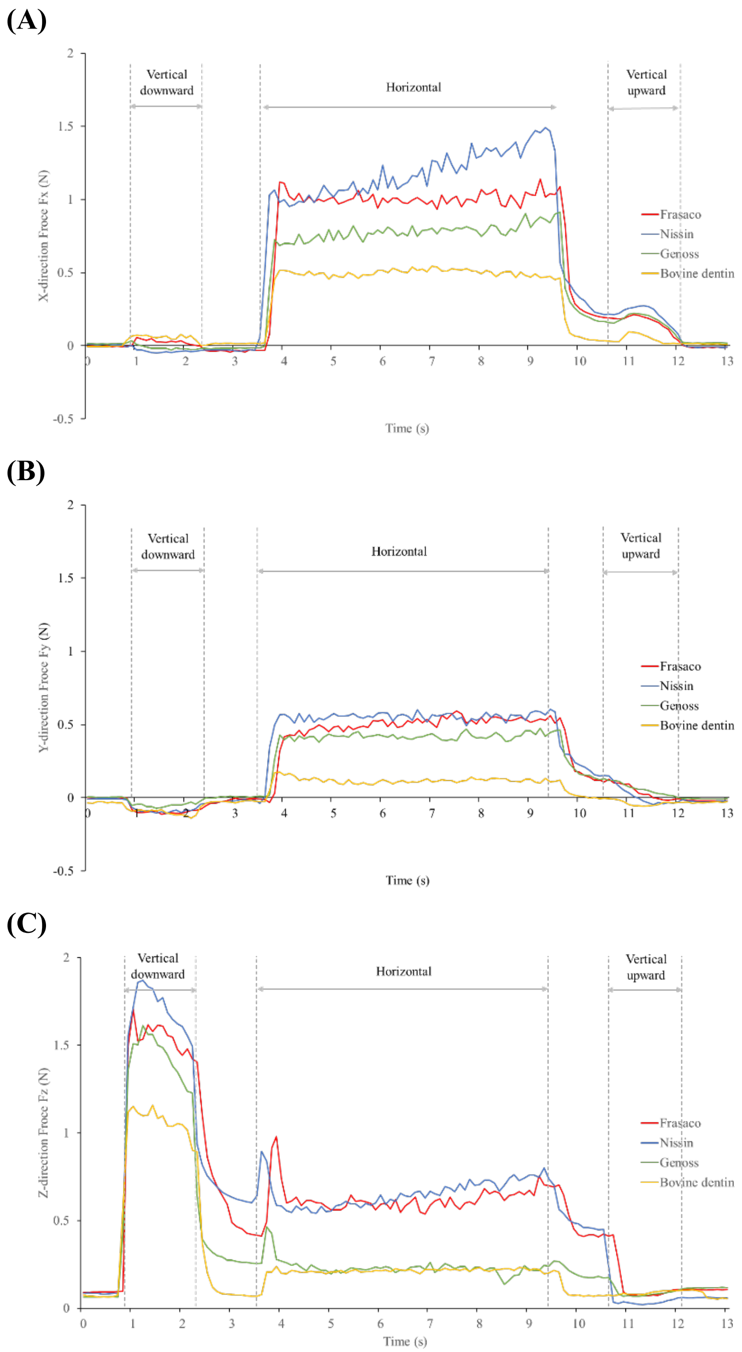

Figure 4. The real-time cutting force variations graph across three axes: (A) X-direction force, (B) Y-direction force, (C) Z-direction force.

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3.2. Comparison of cutting force according to group

3.2.1. Vertical-downward movement

Median cutting forces during vertical-downward movement were compared between dental training teeth and bovine dentin (Fig. 5). A one-way ANOVA was conducted to assess statistical differences among the tested groups. The analysis revealed that the Fy component did not exhibit a statistically significant variation (F = 2.814, p = 0.045). However, significant differences were observed in the Fx, Fz, and Fr components (Fx: F = 10.073, $p < 0.001$; Fz: F = 24.933, $p < 0.001$; Fr: F = 25.141, $p < 0.001$).

Tukey's post hoc test revealed that no statistically significant differences in the X-axis cutting forces (Fx) were found among Frasaco (0.007 ± 0.03 N), Nissin (−0.015 ± 0.03 N), and Genoss (−0.014 ± 0.02 N) ($p > 0.05$), while Bovine dentin exhibited significantly higher values than all dental training teeth ($p < 0.05$) (Fig. 5A). Similarly, the Y-axis cutting forces (Fy) did not differ significantly among the groups ($p > 0.05$) (Fig. 5B). In contrast, the Z-axis cutting forces (Fz) showed significant differences across most groups, except for Frasaco (1.638 ± 0.23 N) and Nissin (1.729 ± 0.33 N), which were not statistically different (p = 0.721) (Fig. 5C). The resultant force (Fr), calculated as the vector sum of Fx, Fy, and Fz, exhibited a statistically similar pattern to that of Fz: significant differences were observed among most groups, except between Frasaco (1.641 ± 0.23 N) and Nissin (1.732 ± 0.33 N), which also showed no statistical difference (p = 0.714) (Fig. 5D).

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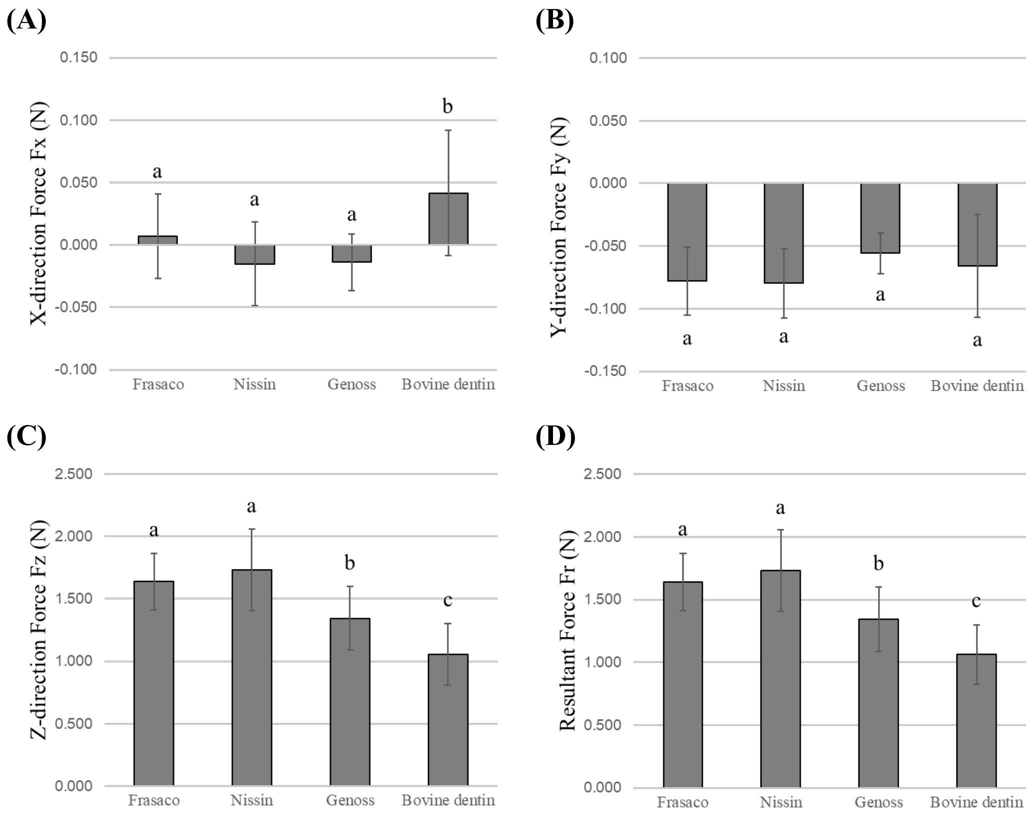

Figure 5. Three-axis force comparison graphs for measured forces during dynamic cutting in vertical-downward movement. Forces in the (A) X-direction, (B) Y-direction, (C) Z-direction (D) Resultant force.

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3.2.2. Horizontal movement

Median cutting forces during horizontal movement were compared between dental training teeth and bovine dentin (Fig. 6). A one-way ANOVA was conducted to assess statistical differences among the tested groups. The analysis revealed that statistically significant differences were observed across all measured force components (Fx: F = 43.550, $p < 0.001$; Fy: F = 94.789, $p < 0.001$; Fz: F = 120.085, $p < 0.001$; Fr: F = 87.048, $p < 0.001$).

Tukey's post hoc test revealed that significant differences in the X-axis cutting forces (Fx) were observed among the groups, except between Nissin (1.192 ± 0.22 N) and Frasaco (1.027 ± 0.24 N, $p = 0.052$), and between Frasaco and Genoss (0.887 ± 0.17 N, $p = 0.127$) (Fig. 6A). Similarly, significant differences in the Y-axis cutting forces (Fy) were observed among the groups, except between Nissin (0.522 ± 0.06 N) and Frasaco (0.465 ± 0.07 N, $p = 0.052$), and between Frasaco and Genoss (0.444 ± 0.05 N, $p = 0.760$) (Fig. 6B). Regarding the Z-axis cutting forces (Fz), all groups showed significant differences except Frasaco (0.635 ± 0.12 N) and Nissin (0.683 ± 0.11 N), which were not statistically different ($p = 0.427$) (Fig. 6C). The resultant force (Fr), calculated as the vector sum of Fx, Fy, and Fz, exhibited a comparable statistical pattern to Fz, with significant differences observed between all material groups ($p < 0.05$) (Fig. 6D).

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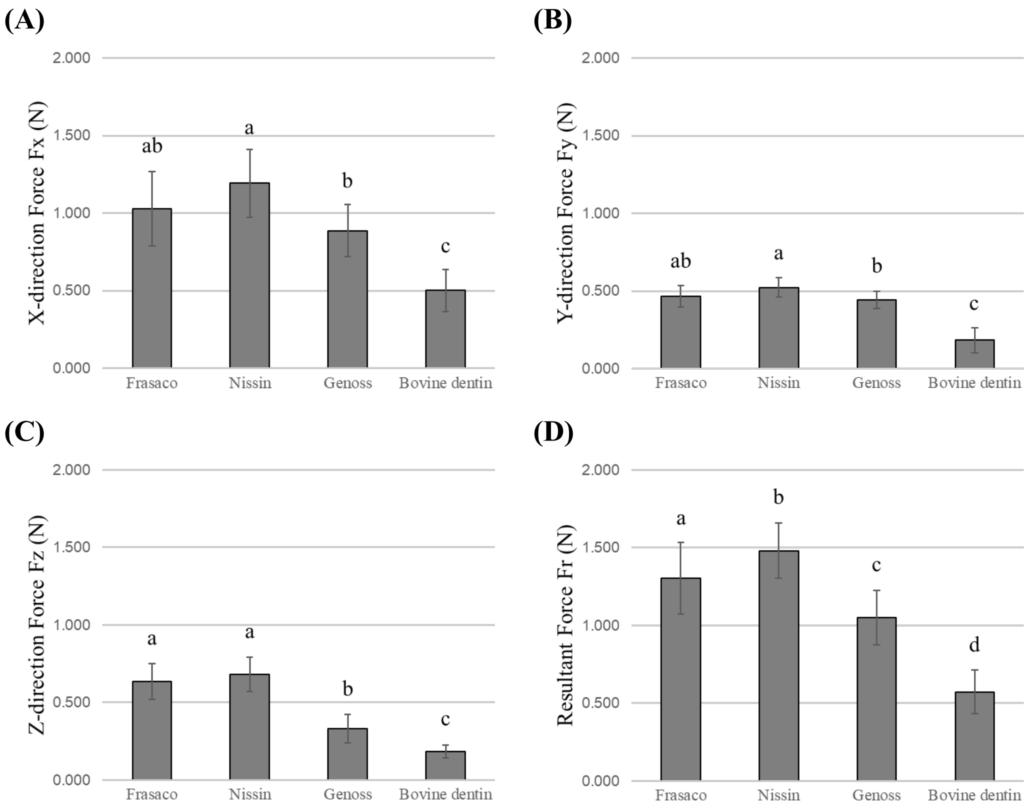

Figure 6. Three-axis force comparison graphs for measured forces during dynamic cutting in horizontal movement. Forces in the (A) X-direction, (B) Y-direction, (C) Z-direction (D) Resultant force.

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3.2.3. Vertical-upward movement

Median cutting forces during vertical-upward movement were compared between dental training teeth and bovine dentin (Fig. 7). A one-way ANOVA was conducted to assess statistical differences among the tested groups. The analysis revealed that significant differences were observed in all measured force components, including Fx, Fy, Fz, and Fr (Fx: $F = 35.840$, $p < 0.001$; Fy: $F = 31.805$, $p < 0.001$; Fz: $F = 6.178$, $p < 0.001$; Fr: $F = 27.272$, $p < 0.001$).

Tukey's post hoc test revealed that significant differences in the the X-axis cutting forces (Fx) were observed among the groups, except between Nissin (0.203 ± 0.08 N) and Frasaco (0.170 ± 0.04 N, $p = 0.240$), and between Frasaco and Genoss (0.139 ± 0.03 N, $p = 0.262$) (Fig. 7A). For the Y-axis cutting forces (Fy), no statistically significant differences were found among Frasaco (0.009 ± 0.02 N), Nissin (0.003 ± 0.03 N), and Genoss (0.007 ± 0.02 N) ($p > 0.05$), with significant differences observed only in comparisons involving Bovine dentin, which showed higher values than all dental training teeth ($p < 0.05$) (Fig. 7B). Similarly, the Z-axis cutting forces (Fz) did not differ significantly among Nissin (0.061 ± 0.04 N), Genoss (0.062 ± 0.03 N), and Bovine dentin (0.059 ± 0.03 N) ($p > 0.05$), while Frasaco exhibited significantly higher values than the others ($p < 0.05$) (Fig. 7C). The resultant force (Fr), calculated as the vector sum of Fx, Fy, and Fz, showed a comparable statistical pattern to Fz, with significant differences found among most groups except between Frasaco (0.199 ± 0.03 N) and Nissin (0.218 ± 0.07 N, $p = 0.529$) (Fig. 7D).

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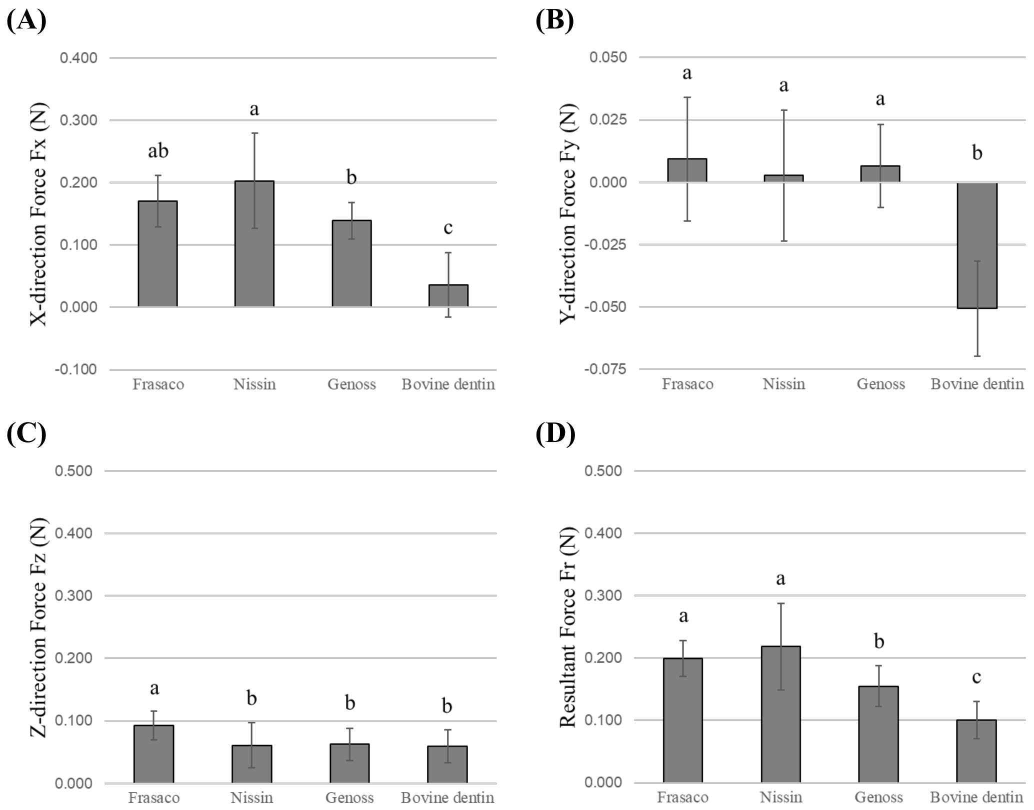

Figure 7. Three-axis force comparison graphs for measured forces during dynamic cutting in vertical-upward movement. Forces in the (A) X-direction, (B) Y-direction, (C) Z-direction (D) Resultant force.

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3.3. SEM observation

3.3.1 Bur wear and cutting debris

After dynamic cutting experiments, SEM analysis revealed that at ×100 magnification, cutting debris was observed in most material groups, and no visible wear or structural damage was identified on the bur surface. However, at ×300 magnification, fine chipping and wear were identified on the cutting edges of carbide burs that were used to cut Frasaco and Nissin, as indicated by red arrows in the SEM images. In contrast, such wear patterns were not prominently observed in burs interacting with other groups under the same magnification. These findings suggest that Frasaco and Nissin tend to cause greater physical damage to the cutting edges of dental burs compared to other groups (Fig. 8).

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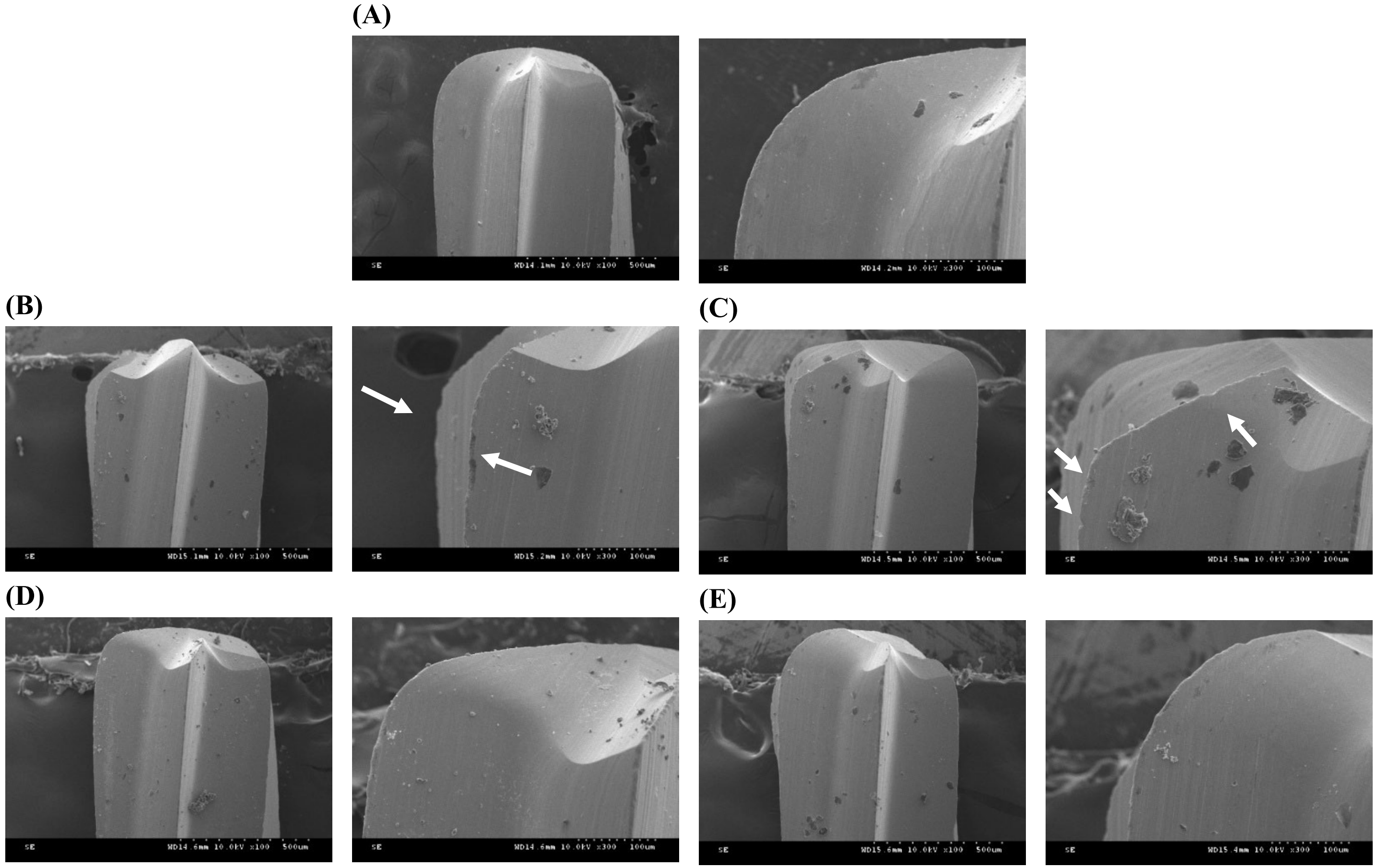

Figure 8. SEM analysis (×100 and ×300) of carbide burs carbide burs used once per sample after dynamic cutting with dental training teeth and bovine dentin. (A) New bur; (B) Frasaco; (C) Nissin; (D) Genoss; (E) Bovine dentin. Cutting debris was observed on most burs, while bur wear was specifically noted in Frasaco and Nissin (arrows).

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3.3.2. Surface characteristics after cutting sample

The surface characteristics of the tested groups after dynamic cutting was analyzed using SEM at magnifications of ×500 and ×1,500. The analysis focused on surface roughness, residual debris, and patterns of bur marks or damage. Distinct differences were observed between dental training teeth and bovine dentin in both vertical-downward movement and horizontal movement processes.

SEM analysis identified common surface characteristics following vertical-downward movement. All three dental training teeth groups (Frasaco, Nissin, Genoss) exhibited similar patterns of micro-cracks, fractures, and debris accumulation (Fig. 9A-C). In contrast, bovine dentin exhibited smoother and more uniform surfaces with minimal debris (Fig. 9D).

SEM analysis identified shared surface characteristics among dental training teeth following horizontal movement. All three dental training teeth groups (Frasaco, Nissin, Genoss) exhibited similar bur traces, noticeable debris, and irregular cutting patterns, with no significant differences observed among them (Fig. 10A-C). In contrast, bovine dentin exhibited a smooth and uniform surface with clearly defined horizontal movement traces, indicating more consistent material removal (Fig. 10D).

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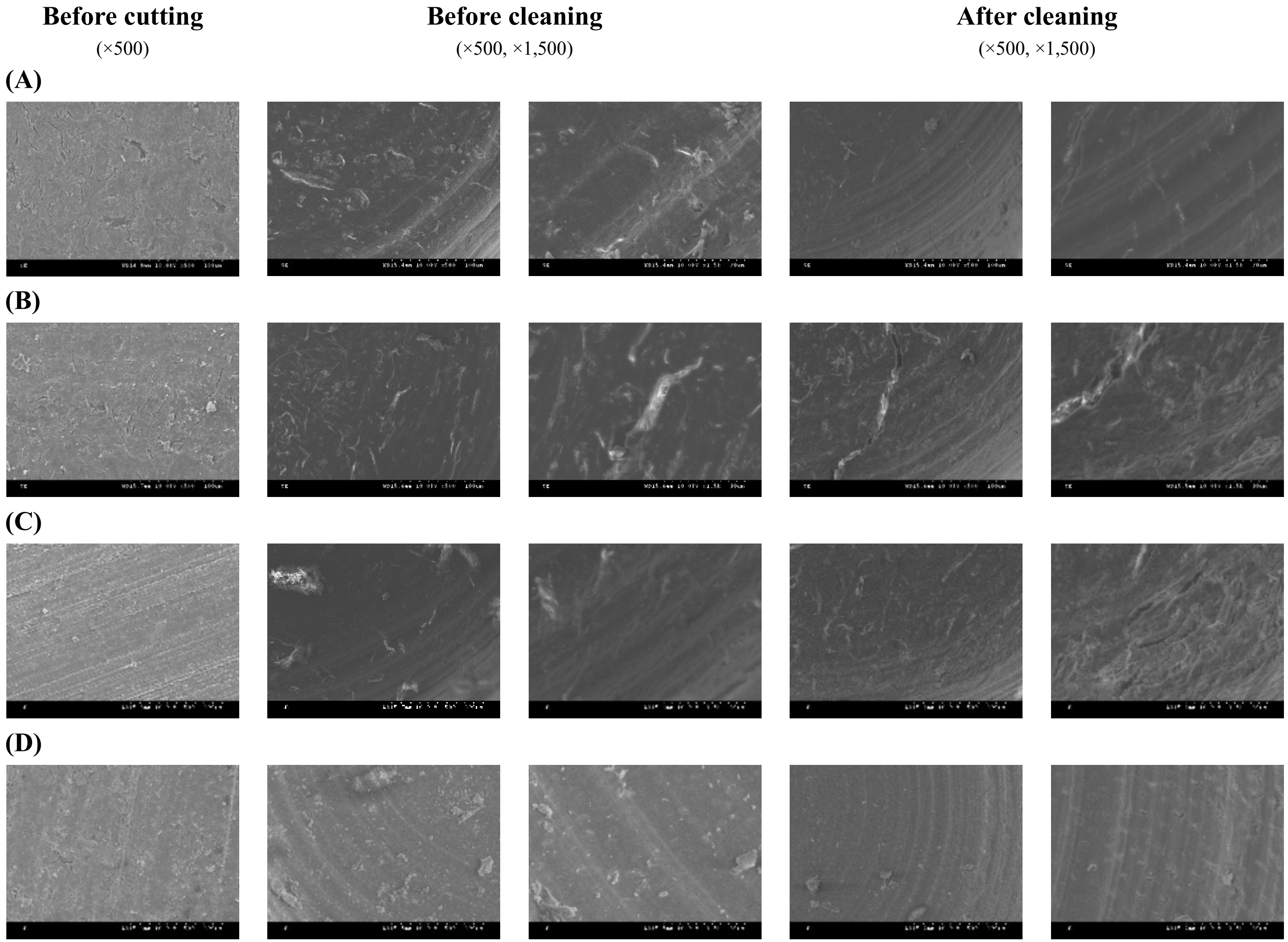

Figure 9. SEM image (×500 and ×1,500) of the cutting surface after vertical-downward movement of different groups. Images were taken under three conditions: (1) prior to cutting after surface polishing, (2) after cutting without debris removal, and (3) after ultrasonic cleaning to remove debris. (A) Frasaco; (B) Nissin; (C) Genoss; (D) Bovine dentin.

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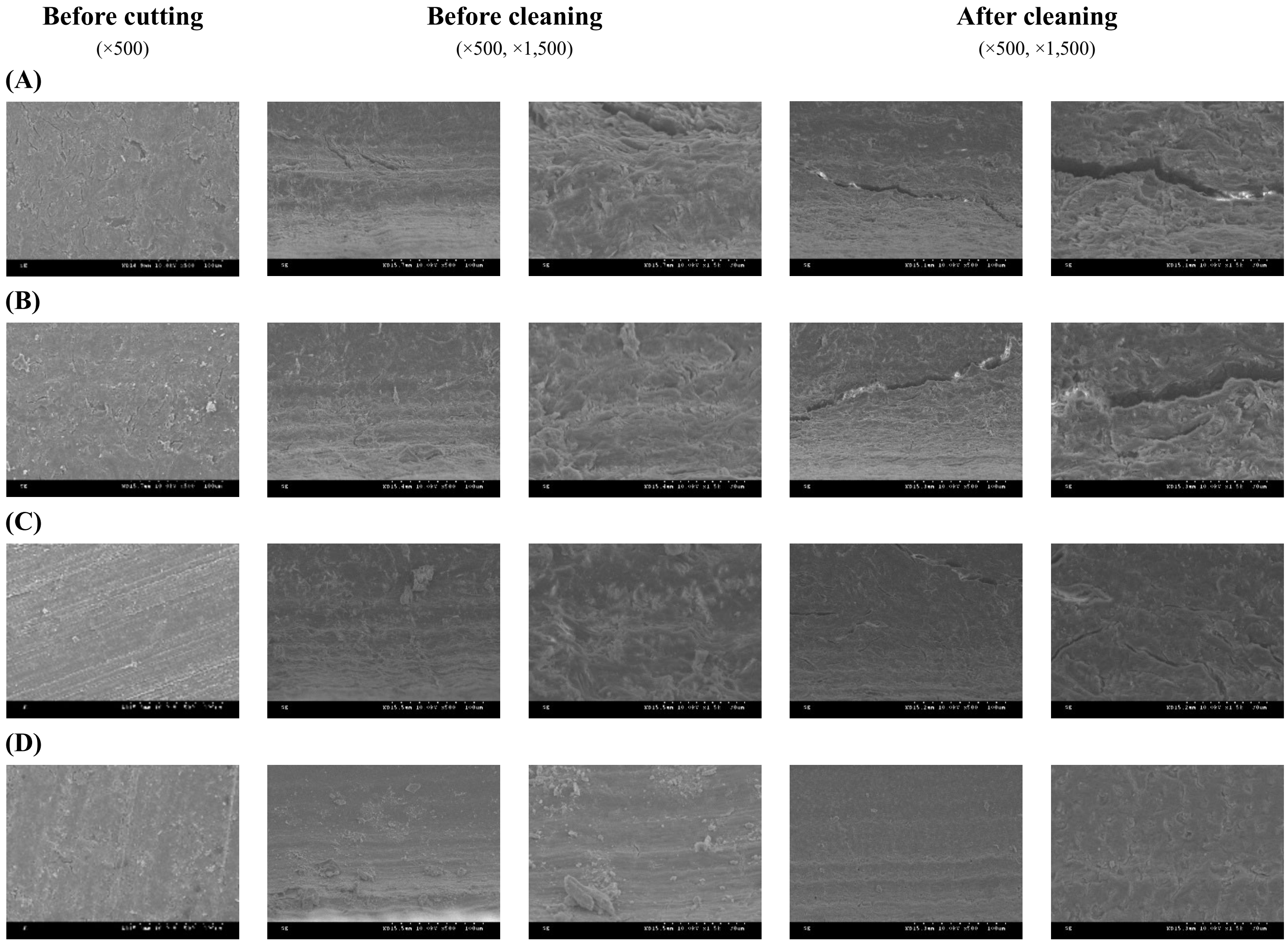

Figure 10. SEM image (×500 and ×1,500) of the cutting surface after horizontal movement of different groups. Images were taken under three conditions: (1) prior to cutting after surface polishing, (2) after cutting without debris removal, and (3) after ultrasonic cleaning to remove debris. (A) Frasaco; (B) Nissin; (C) Genoss; (D) Bovine dentin.

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4. Discussion

The objective of this study was to compare the mechanical properties of three types of dental training teeth (Frasaco, Nissin, Genoss) with those of bovine dentin. In clinical practice, dentists perceive resistance through tactile feedback while preparing teeth, adjusting the handpiece’s direction, pressure, and speed accordingly. This cutting sensation enables fine motor adjustments critical for precision-based tasks such as cavity and crown margin preparation (Elias et al., 2003). However, subjectively perceived tactile feedback may introduce variability in assessment, underscoring the need for a more objective and quantifiable evaluation (Reymus et al., 2020).

This study aimed to address methodological and material limitations identified in previous research. From a methodological perspective, Vickers hardness tests and static load applications have been used to analyze cutting forces, while SEM has been applied to assess bur wear and surface characteristics (Tokunaga et al., 2022). Additionally, nano-indentation testing has been used to measure elastic modulus and hardness, while subjective evaluations of cutting sensation and additional SEM analysis have also been conducted (He et al., 2012). These studies primarily rely on single-axis force measurements or subjective assessments, which have limitations in fully capturing the complex mechanical interactions occurring during dynamic cutting. Static load applications measure force in only one direction, making it difficult to account for real-time variations and multidirectional loading conditions in clinical procedures. In contrast, this study utilized a computer-controlled cutting system equipped with a three-axis load cell to measure dynamic cutting forces (Fx, Fy, Fz) generated during high-speed handpiece operation. This approach allowed for multidirectional force acquisition under simulated operative conditions, introducing a complementary approach to earlier studies using static loading or unidirectional force measurements.

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From a material perspective, previous research has primarily compared the mechanical properties of dental training teeth or CAD/CAM blocks. Although CAD/CAM blocks or dental training teeth are monoblocks with uniform structure, natural teeth consist of biologically layered and anisotropic structures, which differ fundamentally in composition and architecture from synthetic materials (Lee et al., 2024). In contrast, this study included bovine dentin as a biological reference material. Bovine dentin, commonly used as a structural and mechanical analog to human dentin, provided a basis for evaluating the relative mechanical behavior of training materials in comparison to a more biologically representative substrate.

Cutting force, defined as the reaction force (Fx, Fy, Fz) exerted by the material against the rotating bur during dynamic cutting, is generated as a response to the material's mechanical resistance under high-speed rotary instrumentation. In this study, cutting force was employed as the primary metric to enable quantitative comparison across groups (Elias et al., 2003; Liang et al., 2016). While this force reflects the interaction between the handpiece and the material, it is influenced by both the mechanical properties of the material and the dynamic parameters of the instrumentation. Therefore, it serves as a surrogate indicator of material-dependent cutting resistance under controlled conditions.

The cutting force measured along the Z-axis direction during vertical-downward movement corresponds to the drilling force. Among all groups, Nissin exhibited the highest drilling force, followed by Frasaco, Genoss, and bovine dentin. The drilling force values for Frasaco and Nissin were relatively similar. Bovine dentin recorded the lowest drilling force, while Genoss displayed the smallest value among the dental training teeth. During drilling, the forces in the X- and Y-axes were relatively small and approached zero. Previous studies have reported that the drilling force measured on natural teeth using a round diamond bur is approximately 1.071 ± 0.43 N (Yoshida et al., 2011). In this study, using a carbide bur, a similar force of 1.055 ± 0.25 N was recorded during drilling. However, direct comparison with natural tooth data should be interpreted considering methodological differences, as measured drilling forces are influenced by a combination of factors, including bur geometry,

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feed rate, rotational speed, and other test conditions. A study on enamel-cutting mechanics demonstrated that thrust force increases with higher feed rates. Additionally, carbide fissure burs generate greater thrust force than diamond burs at low feed rates, while the trend reverses at higher feed rates (Zhao et al., 2023).

Groups with greater cutting force, such as Nissin, exhibited a progressive increase in milling force with increasing cutting distance (Fig. 4A). Conversely, groups with lower cutting force, such as bovine dentin, maintained a relatively constant milling force regardless of the cutting distance. A previous study using an air turbine handpiece found that milling force increased with cutting distance, while bur rotation speed decreased (Wu et al., 2020). Unlike air turbines, which experience rpm reductions due to insufficient torque under high resistance, electric handpieces adjust torque to sustain a constant rotational speed (Choi et al., 2010; Ercoli et al., 2009; Fujimaki et al., 2022). In this study, milling force remained relatively stable in most groups as the cutting distance increased, except for those with the highest cutting force, where force continued to rise. This trend suggests that the electric handpiece dynamically adjusted torque in response to variations in cutting force, effectively maintaining a consistent rotational speed. However, in the hardest material, Nissin, the milling force continued to rise with cutting distance. SEM analysis further supported these findings by revealing more pronounced surface wear and debris accumulation in Nissin samples, which corresponded to the continuous increase in milling force with cutting distance. Additionally, images of the carbide bur after cutting showed more severe wear when used on Nissin and Frasaco compared to bovine dentin and Genoss, suggesting that bur degradation may have contributed to the increased cutting force observed in harder groups.

The cutting force along the Z-axis direction decreased rapidly and approached zero during vertical-upward movement. The forces in the X-axis direction (Fx) and Y-axis direction (Fy) were measured during various movements. However, the forces in the X- and Y-axes showed a more gradual decrease while remaining positive, suggesting that resistance was encountered between the bur and the sample as the carbide bur exited the

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sample after cutting and during vertical-upward movement. This resistance may be associated with residual chips (debris) left inside the cavity, which can contribute to increased cutting forces, as reported in previous studies on drilling dynamics (Ramulu et al., 2001; Ramulu et al., 1999). The largest forces in the X-axis direction were observed for Frasaco and Nissin, followed by Genoss, with bovine dentin showing significantly lower forces. A consistent observation across all groups was that the X-axis force (Fx) was approximately twice the magnitude of the Y-axis force (Fy). The resistance in the X-axis direction (Fx) encountered by the carbide bur arises from direct contact with the sample's front and rear walls (i.e., anterior and posterior walls) during forward motion, serving as the primary source of resistance in the cutting process. In contrast, the resistance in the Y-axis direction (Fy) results from opposing forces generated by contact with two lateral walls (i.e., left and right walls) along the Y-axis (Lee et al., 2024). These opposing forces cancel each other out, leading to a net force that is relatively small when measured in the Y-axis. Thus, during the vertical-upward movement, the resistance encountered by the carbide bur is largely influenced by the X-axis resistance, while the Y-axis resistance is minimal.

Although statistically significant differences in cutting forces were observed between groups, their perceptual relevance depends on whether such differences surpass the tactile detection threshold during high-speed instrumentation. Prior investigations have reported that differences in cutting force within the range of 1–2 N were perceivable by dental clinicians and influenced their subjective evaluation of material similarity (Cresswell-Boyes et al., 2025). In the present study, several force differences exceeded 0.5 N across movement directions. While this magnitude may fall below the tactile detection threshold in high-speed instrumentation, it suggests potential for perceptual relevance under certain conditions and supports the need for further investigation into its clinical detectability.

In this study, groups that exhibited higher cutting forces, particularly in the X-axis direction, showed increased mechanical stress during cutting. Additionally, as cutting distance increased, material-dependent variations in cutting force became more pronounced. This resistance may contribute to tool wear, highlighting the need for further

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investigation into its long-term effects on carbide burs. Higher cutting forces were observed in groups such as Frasaco and Nissin, which corresponded with greater surface wear on carbide burs, particularly on the cutting edges. Increased cutting force in these high-density groups required greater force application, leading to enhanced friction and thermal stress, factors known to contribute to bur degradation over time (Reisbick & Bunshah, 1973; Tanaka et al., 1991). Additionally, high cutting speeds and insufficient cooling exacerbated these effects, further reducing bur lifespan. To mitigate these risks, clinicians may consider strategies such as optimizing cutting speed, using intermittent cutting with adequate cooling, adjusting cutting pressure, selecting burs suitable for high-resistance groups, and ensuring regular bur replacement (Cavalcanti et al., 2002; Wu et al., 2020).

This study has several limitations. First, bovine teeth were used instead of human teeth, which may differ in microstructural and mechanical properties (Cresswell-Boyes et al., 2022; Nowak & Samuel, 2019). Second, only the dentin layer was tested, excluding the enamel and failing to replicate the enamel–dentin structure of a natural tooth (Ohmoto et al., 1994; Tanaka et al., 1991). Third, cutting was performed under fixed movement directions, feed rate, and rotational speed, which do not fully reflect the variability of clinical cutting conditions (Choi et al., 2010; Fujimaki et al., 2022; Song et al., 2015; Song & Yin, 2012). Fourth, only one type of carbide bur was used, whereas clinical settings involve multiple bur types and progressive bur wear (Ben-Hanan et al., 2008; Di Cristofaro et al., 2013; Funkenbusch et al., 2015). Fifth, other dynamic mechanical factors such as torque and vibration were not assessed, despite their potential influence on tactile feedback (Korkmaz et al., 2015; Zhao et al., 2016). Finally, this study did not include quantitative measurements of intrinsic material properties, such as hardness or elastic modulus, which may affect cutting performance and surface response (Chuenarrom et al., 2009; Hughes & White, 2009; Zafar & Ahmed, 2013).

To address these limitations, First, the use of extracted human teeth may better reflect the biological and structural characteristics of natural dentition. Second, including both enamel and dentin layers in the specimens may enable a more comprehensive evaluation of cutting behavior across the tooth's layered structure. Third, cutting conditions and

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instrumentation should be diversified. Differences in cutting performance between high-speed and low-speed handpieces, as well as electric versus air-turbine systems, need to be investigated. Moreover, variations in cutting angles, depths, and feed rates should be systematically evaluated to better clinical cutting conditions. Fourth, future studies should include a wider range of rotary instruments beyond carbide burs. Comparisons involving diamond burs and other clinically relevant instruments, along with the progressive effects of bur wear through repeated use, will yield more comprehensive insights into clinical performance. Fifth, dynamic mechanical responses—including torque, torsional moment, and vibration—should be assessed using precision measurement tools such as 6-axis force/torque sensors, dynamometers, and vibration analyzers. Incorporating these modalities will enable a more comprehensive evaluation of cutting dynamics during cutting. Finally, quantitative characterization of material properties should be introduced. Techniques such as nanoindentation, Vickers or Knoop hardness testing, and crack propagation evaluation can provide deeper understanding of mechanical resistance and failure behavior. Such data would enhance the interpretive power of cutting force measurements and surface characteristics analysis.

This study provides empirical data on cutting mechanics and the performance of dental training groups, offering an objective assessment of cutting force. The observed material-dependent variations in cutting force serve as an objective indicator of the discrepancy between preclinical simulations and clinical reality, offering insight into how dental training should be adapted to address this gap. While dental training teeth cannot fully replicate the tactile properties of natural teeth, recognizing this limitation during preclinical exercises may help learners calibrate their expectations and better prepare for clinical variability. The quantitative differences demonstrated in this study serve not only as objective evaluation criteria, but also as potential tools for reflective learning in simulation-based dental education.

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5. Conclusion

This study confirmed that dental training teeth exhibited distinct mechanical responses compared to bovine dentin. Frasaco and Nissin showed higher cutting forces, visible bur wear, and rougher cut surfaces. Genoss exhibited intermediate cutting forces, showed no observable bur wear, and shared surface characteristics with other dental training teeth. In contrast, bovine dentin showed the lowest cutting forces, no bur wear, and smoother post-cutting surfaces.

1. For vertical-downward movement, the resultant force was lowest in the bovine dentin group among all tested groups, while Genoss exhibited the lowest force among the dental training teeth.

2. For horizontal movement, the resultant force was highest in Nissin, followed by Frasaco and Genoss, while bovine dentin exhibited the lowest force among all tested groups.

3. For vertical-upward movement, the resultant force was the lowest for bovine dentin among all material groups, while Genoss showed the lowest force within the dental training teeth material group.

4. SEM analysis revealed that cutting with Frasaco and Nissin resulted in visible wear and fine chipping on the cutting edges of carbide burs, whereas such damage was not observed in the burs used with bovine dentin. Surface characteristics analysis further showed that bovine dentin exhibited smoother and more uniform surfaces with minimal debris, while dental training teeth showed micro-cracks, fractures, and debris accumulation.

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Abstract in Korean

모션 제어 동적 절삭 시 치과 훈련용 치아와 우치 상아질의 기계적 거동: 3축 하중 측정 및 SEM 분석을 사용한 연구

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전임상 치의학 교육에서 지대치 형성을 포함한 다양한 치아 삭제 술식을 재현하기 위해 치과 훈련용 치아가 널리 사용된다. 치과 훈련용 치아는 합성수지 기반의 재료로 제작되며, 조성 및 기계적 특성에서 자연치와 차이를 보인다. 치과 훈련용 치아는 교육 환경에서 널리 사용되었으나 기존 연구들은 주로 단축 하중 기반의 절삭력 측정이나 정성적 분석에 국한되어 있어, 실제 임상 상황에서 나타나는 복잡한 기계적 반응을 충분히 반영하지 못하는 한계가 있다. 본 연구에서는 이러한 한계를 보완하기 위해, 임상 절삭 환경을 모사한 조건에서 치과 훈련용 치아와 우치 상아질 간의 절삭 저항 특성을 3축 힘 측정 시스템을 통해 정량적으로 평가하였다.

본 연구는 고속 치과용 핸드피스를 이용한 컴퓨터 제어식 동적 절삭 시스템과 3축 로드셀을 이용해 수직 하향 1.5 mm, 수평 6 mm, 수직 상향 1.5 mm 의 세 가지 절삭 방향에서 절삭력을 측정하였으며, 모든 절삭은 이송 속도 1 mm/s, 회전 속도 200,000 rpm 의 조건에서 수행되었다. 절삭 이후,

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SEM 분석을 통해 절삭된 시편의 표면과 사용된 절삭 버의 마모 상태를 관찰하였다.

통계 분석은 일원분산분석(one-way ANOVA)과 사후 Tukey 검정을 통해 수행되었다. 수직 하향 운동시 프라사코와 닛신이 우치 상아질보다 유의하게 높은 합력(Fr) 값을 보였으며($p < 0.001$), 두 재료 간에는 유의한 차이가 나타나지 않았다($p = 0.714$). 수평방향 운동시 모든 훈련용 치아가 우치 상아질보다 유의하게 높은 합력 값을 나타냈고($p < 0.001$), 훈련용 재료 간의 쌍 비교에서도 유의한 차이가 관찰되었다($p < 0.05$). 수직 상향 운동시 프라사코와 제노스가 우치 상아질보다 유의하게 높은 합력 값을 보였으며($p < 0.001$), 프라사코와 닛신간에는 유의한 차이가 없었다($p = 0.529$). 이와 같은 결과는 조건이 통제된 동적 절삭 조건에서 재료별 절삭 저항성에 차이가 있음을 정량적으로 확인하였다. 이 결과를 통해 우치 상아질이 모든 절삭 방향에서 상대적으로 낮은 절삭 저항을 나타냄을 시사한다.

버에 대한 SEM 분석 결과(×100 및 ×300), 프라사코 및 닛신 치과 훈련용 치아를 절삭한 후의 카바이드 버에서는 미세한 파절과 절삭날 마모가 관찰되었으나, 우치 상아질을 절삭한 버에서는 이와 유사한 마모가 나타나지 않았다. 절삭된 시편 표면에 대한 SEM 분석(×500 및 ×1,500)결과, 치과 훈련용 치아 3 종에서 미세균열, 파절, 이물질 축적이 관찰되었으며, 우치 상아질은 상대적으로 매끄럽고 결함이 적은 표면 특성을 보였다.

본 연구는 컴퓨터 제어식 동적 절삭 시스템에서 치과 훈련용 치아와 우치 상아질 간의 기계적 거동 차이를 규명하였다. 치과 훈련용 치아는 상대적으로 높은 절삭 저항과 표면 손상을 보였으며, 우치 상아질은 낮은 절삭 저항과 더 부드러운 절삭면 특성을 나타냈다. 본 연구는 모의 동적 절삭 환경에서 두 재료 그룹 간의 기계적 차이에 대한 정량적 증거를 제공하였으며, 절삭 힘

측정과 SEM 분석을 통해 이를 확인하였다. 이러한 재료 기계적 특성의 차이는 교수자와 학생이 교육 과정 중에 반드시 인식해야 할 요소로, 단순히 자연치와 동등하다고 가정하기보다는 이러한 한계를 이해하고 교육 실습을 설계하고 수행하여 학생이 임상 실습에 대비하여 적절한 기대치를 갖고 훈련하여 임상 환경에 효과적으로 대비할 수 있도록 해야 할 것이다.

핵심되는 말: 3축 로드셀, 고속 핸드피스, 주사전자현미경 (SEM), 절삭력, 우치 상아질, 치과 훈련용 치아