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ORIGINAL RESEARCH

Fracture resistance of direct composite and digitally fabricated endocrowns in pulpotomized primary molars: an *in vitro* study

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Abstract

Background: Restoring extensively damaged primary molars remains challenging due to the limitations of conventional materials. Although digitally fabricated endocrowns are a potential alternative, their mechanical performance in primary teeth remains underexplored. This study aimed to compare the fracture resistance and failure modes of direct composite and digitally fabricated endocrowns in pulpotomized primary molars. **Methods**: Forty extracted human maxillary second primary molars were randomly allocated into four groups (n = 10): direct composite, milled resin-matrix ceramic, milled composite, and three-dimensional (3D)-printed resin. Following pulpotomy procedures, standardized endocrown preparations were performed. In the direct composite group, restorations were placed using conventional composite resin, while in the remaining groups, endocrowns were digitally fabricated through computer-aided design and computer-aided manufacturing (CAD/CAM) milling or 3D printing and adhesively cemented. Fracture resistance was evaluated using a universal testing machine until fracture occurred. Failure loads and modes were recorded. Data were analyzed using one-way analysis of variance (ANOVA), Tukey's Honest Significance Difference (HSD), and chi-square tests ($p < 0.05$). **Results**: Fracture resistance differed significantly among groups ($p < 0.05$). Milled resin-matrix ceramic exhibited the highest fracture resistance (1572.42 ± 265.67 N), followed by milled composite (1494.00 ± 360.85 N), direct composite (1211.09 ± 300.76 N), and 3D-printed resin (1068.14 ± 199.67 N). The milled resin-matrix ceramic group demonstrated significantly higher fracture resistance than the direct composite and 3D-printed groups. Compared with the 3D-printed group, the milled composite group also exhibited significantly higher fracture resistance ($p < 0.05$). No significant differences were observed among the remaining comparisons. Failure mode distribution did not differ significantly among groups ($p > 0.05$). **Conclusions**: Resin-matrix ceramic endocrowns showed the highest fracture resistance. All tested materials exceeded average masticatory forces in children, suggesting that digitally fabricated endocrowns may serve as a minimally invasive and aesthetic restorative option for pulpotomized primary molars.

Keywords

Primary molars; Endocrowns; CAD-CAM; Additive manufacturing; Fracture resistance; Composite resin; Digital dentistry

1. Introduction

Primary molars play a key role in maintaining function and arch integrity during childhood [1]. However, when affected by extensive caries, they often exhibit substantial structural loss, compromising their mechanical integrity and resistance to fracture [2]. Following pulp therapy, the remaining tooth structure is further weakened, exacerbating the risk of restoration failure under functional loading [3]. Therefore, restoration of such teeth remains a clinical challenge in pediatric dentistry, requiring materials and techniques that provide adequate strength while preserving as much tooth structure as possible, all while meeting increasing aesthetic demands.

Traditionally, treatment options for pulpotomized primary molars have included direct restorations and full-coverage approaches such as stainless-steel crowns (SSCs) [4, 5]. Although direct composite restorations offer superior aesthetic value, they are technique-sensitive and require strict moisture control, particularly among young or uncooperative patients. Stainless-steel crowns are considered the gold standard for restoring primary molars following pulp therapy; however, they are limited by poor aesthetic value and potential periodontal concerns [6, 7]. To overcome these limitations, aesthetic full-coverage alternatives, such as open-faced SSCs, chairside veneered SSCs, pre-veneered SSCs (PVSSCs), and prefabricated zirconia crowns (PZCs), have been introduced [8–11]. Despite improved aesthetics, these options often require extensive tooth preparation, may involve multiple appointments, and are associated with higher costs [10–14]. Consequently, there is a growing demand for restorative strategies that balance durability, aesthetics, minimal invasiveness, and reduced clinical time.

The paradigm shift toward minimally invasive dentistry (MID) emphasizes the preservation of sound dental tissue through adhesive restorative approaches [15]. Given this context, endocrowns—monolithic adhesive restorations that rely on both macromechanical retention from the pulp chamber walls and micromechanical retention through adhesive resin cements [16]—have emerged as a conservative treatment option for restoring extensively damaged teeth [17]. Utilizing the pulp chamber allows for a more conservative preparation while preserving critical dentin structure, which is particularly advantageous for pediatric patients, in whose cases pulp chambers are proportionally larger and enamel is thinner.

Endocrowns are especially indicated in cases of extensive coronal tissue loss or limited interocclusal space, where conventional crown preparation may be compromised. They may also be considered in situations with high aesthetic demands and when adequate isolation can be achieved in primary teeth [18]. However, although endocrowns have been extensively studied in permanent dentition, their application in pulpotomized primary molars remains limited. Thus, given the structural differences of primary teeth and the importance of preserving their function, further investigation in pediatric populations is required [19].

Advances in computer-aided design and computer-aided manufacturing (CAD/CAM) technologies have enabled the fabrication of indirect restorations with improved marginal adaptation and reduced chair time, which is particularly advantageous in pediatric dentistry [20–23]. Milling-based subtractive manufacturing systems allow for the use of various materials, including zirconia, resin-matrix ceramics, and composite blocks [24–26]. Among these, millable resin-based materials are considered more suitable for primary teeth due to their lower hardness and elastic modulus, which help reduce antagonist wear and absorb functional stresses [24–28].

In addition to subtractive methods, additive manufacturing has recently emerged as an alternative approach in restorative dentistry. For instance, 3D printing enables the production of restorations with complex geometries, reduced material waste, and cost efficiency, making it a promising option in pediatric applications [29, 30]. Moreover, newly developed permanent resin materials for 3D printing have demonstrated encouraging mechanical and clinical performance [31–33].

Fracture resistance is a critical factor affecting the longevity and functional success of restorations in pulpotomized primary molars [34]. Therefore, the ability of restorative materials to withstand masticatory forces is crucial to clinical success. Recent studies have evaluated the fracture resistance of various restorative options for primary molars, including CAD/CAM-fabricated endocrowns [34–36]. While these studies report clinically acceptable fracture resistance values, they predominantly focus on subtractive manufacturing techniques. Evidence regarding the performance of 3D-printed endocrowns remains limited. Thus, this *in vitro* study aimed to compare the fracture resistance and failure modes of direct composite and digitally fabricated (CAD-CAM and 3D-printed) endocrowns in pulpotomized primary molars to better understand their mechanical performance and potential clinical applicability. The null hypothesis was that there would be no statistically significant differences in fracture resistance values or failure modes among the groups.

2. Methods

This *in vitro* study was conducted under standardized laboratory conditions to evaluate the performance of direct composite and digitally fabricated endocrown restorations in pulpotomized primary molars. The experimental workflow included specimen selection, pulpotomy procedures, endocrown preparation, restoration fabrication, adhesive cementation, fracture resistance testing, and failure mode assessment.

The study protocol was approved by the Clinical Research Ethics Committee of Istanbul University Faculty of Dentistry (Approval No: 2023/49; 07 December 2023). Extracted teeth were collected with informed consent from the patients' legal guardians and used in accordance with ethical guidelines involving biological materials. The study was conducted between May 2024 and February 2025.

2.1 Sample size calculation

The sample size was determined using the G*Power software (v3.1.9.4, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, NRW, Germany). Based on an effect size (d) of 0.578, a standard deviation of 105.5, $\alpha = 0.05$, and a power of 0.80, the minimum required sample size was calculated as n = 10 per group, resulting in a total of 40 specimens.

2.2 Specimen selection and storage

Forty extracted human maxillary second primary molars were included in this *in vitro* study. The teeth were collected from pediatric patients aged 6–12 years, for whom extraction was clinically indicated by a pediatric dentist due to physiological exfoliation timing or orthodontic and periodontal reasons. Informed consent for the use of extracted teeth in research was obtained from the patients' legal guardians.

Teeth presenting caries, restorations, cracks, structural defects, previous endodontic treatment, or physiological root resorption exceeding two-thirds of the root were excluded. To ensure specimen standardization, only teeth with similar root morphology and comparable buccolingual and mesiodistal dimensions were included, with a maximum variation of approximately ±1 mm, as verified using a digital caliper. All included teeth had sufficient coronal structure to allow standardized endocrown preparation.

Following extraction, soft tissue remnants were removed, and the teeth were stored in 0.1% thymol solution for 24 hours and subsequently kept in distilled water until use.

Each tooth was embedded vertically in autopolymerizing acrylic resin (Self Cure, IMICRYL Dental Materials, Konya, Turkey) up to 2 mm below the cemento–enamel junction (CEJ) to simulate the alveolar bone level and standardize specimen positioning during testing (Fig. 1).

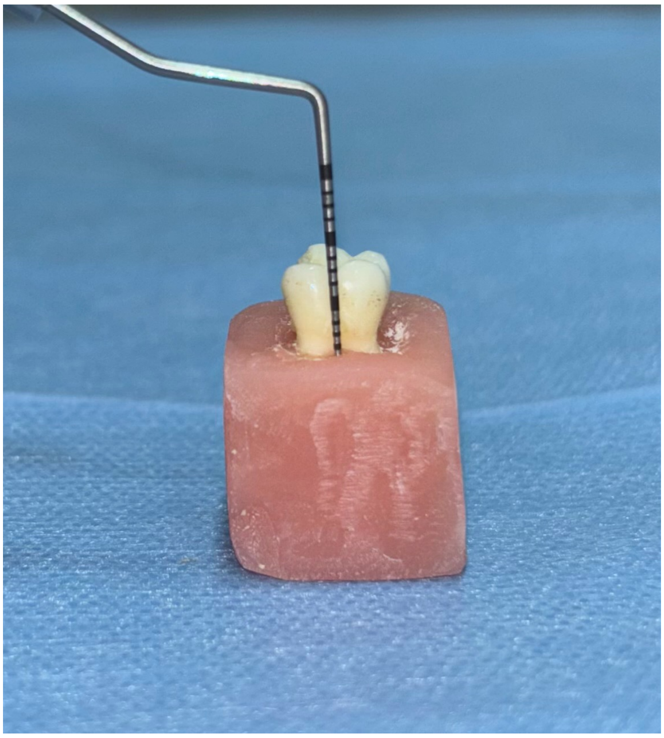


FIGURE 1. Embedding of the primary molar specimen 2 mm below the cemento-enamel junction.

2.3 Specimen grouping

The specimens were randomly assigned to four groups (n = 10) according to the restorative material. The restorative materials used in the study, their primary characteristics, fabrication techniques, and restoration types of the experimental groups are summarized in Table 1.

- Group 1: Direct composite endocrowns (Essentia Universal, GC Corp., Tokyo, Japan).
- Group 2: Milled resin-matrix ceramic endocrowns (Cerasmart 270, GC Corp., Tokyo, Japan).
- Group 3: Milled composite endocrowns (Tetric CAD, Ivoclar Vivadent, Schaan, Liechtenstein).
- Group 4: 3D-printed resin endocrowns (VarseoSmile Crown Plus, BEGO, Bremen, HB, Germany).

2.4 Pulpotomy procedure

Standardized pulpotomy was performed in all specimens. After complete pulp chamber access, a 2-mm layer of zinc oxide-eugenol cement (Dentsply Sirona, Konstanz, BW, Germany) was placed, followed by 2 mm of conventional glass ionomer cement (RIVA Self Cure, SDI Limited, Bayswater, VIC, Australia).

2.5 Endocrown preparation

The endocrown preparation design was established in accordance with previously published studies on endocrowns in primary molars, which emphasize adequate occlusal reduction and the use of the pulp chamber for retention [36].

Standardized endocrown cavity preparations were performed in all specimens under water cooling. Occlusal reduction was achieved by creating 2 mm depth-guiding grooves using a round-ended tapered diamond bur (TR-13, Dia-Burs Mani, Japan), followed by the completion of the occlusal reduction with a wheel-shaped diamond bur (WR-13, MANI, Inc., Tochigi, Japan), as illustrated in Fig. 2. Occlusal reduction was performed with a uniform depth of 2 mm to ensure sufficient material thickness. A butt-joint margin design was utilized, characterized by a flat cavosurface angle of approximately 90° without bevel, to provide a stable bonding interface. Additionally, axial walls were prepared with approximately 8° divergence using a tapered diamond bur (TR-12, MANI, Inc., Tochigi, Japan).

The gingival margin was positioned 0.5 mm coronal to the cemento-enamel junction, and the buccolingual width of the gingival step was standardized to 3 mm. Following the pulpotomy procedure, a standardized base was achieved using 2 mm of zinc oxide–eugenol and 2 mm of conventional glass ionomer cement.

Further, internal line angles were rounded using a cylindrical diamond bur to reduce stress concentration and improve restoration adaptation. A single operator performed all preparations to reduce variability, and a periodontal probe (Williams probe) was used to verify all measurements, ensuring consistency across specimens.

2.6 Restoration fabrication

2.6.1 Direct endocrowns

A selective-etch strategy was applied in the direct composite group. The enamel surfaces were etched with 37% phosphoric acid for 30 seconds, followed by thorough rinsing with water spray for 30 seconds and gentle air-drying for an additional 30 seconds. A single coat of universal adhesive (G-Premio Bond, GC Corp., Tokyo, Japan) was applied using a microbrush, gently air-thinned to remove excess solvent, and light-cured for 40 seconds using an LED light-curing unit (D-Light Duo, GC Corp., Tokyo, Japan) with an output intensity of approximately 1200 mW/cm^2.

The composite resin (Essentia Universal, GC Corp., Tokyo, Japan) was placed incrementally in layers not exceeding 2 mm. Each increment was light-cured for 20 seconds to ensure adequate polymerization. Then, the restoration was finished and adjusted to achieve proper occlusal morphology (Fig. 3).

To ensure consistency across all groups, direct composite restorations were designed based on the previously standardized preparation geometry. The occlusal height measured from the central fossa was standardized at 3.5 mm for all specimens, corresponding to the loading point during fracture resistance testing, and was verified using a periodontal probe. Comparable occlusal thickness and overall restoration form were maintained carefully, thereby minimizing geometric vari-

TABLE 1. Restorative materials used in the study and their main characteristics, fabrication techniques, and restoration types of the experimental groups.

Group	Restorative Material	Manufacturer	Material Type	Main Composition	Fabrication Technique	Final Restoration
Group 1	Essentia Universal	GC Corp., Tokyo, Japan	Resin Composite	UDMA-based composite resin	Direct technique	Direct Composite Endocrown
Group 2	Cerasmart 270	GC Corp., Tokyo, Japan	Millable Resin-Matrix Ceramic Block	Nano-ceramic fillers dispersed in a resin matrix	Subtractive manufacturing (CAD-CAM milling)	Milled Resin-Matrix Ceramic Endocrown
Group 3	Tetric CAD	Ivoclar Vivadent, Schaan, Liechtenstein	Millable Composite Block	Highly cross-linked composite resin	Subtractive manufacturing (CAD-CAM milling)	Milled Composite Endocrown
Group 4	VarseoSmile Crown Plus	BEGO, Bremen, Germany	3D-Printable Resin	Methacrylate-based ceramic-filled photopolymer resin	Additive manufacturing (3D printing)	3D-Printed Resin Endocrown

CAD-CAM: computer-aided design and computer-aided manufacturing; UDMA: Urethane Dimethacrylate; 3D: three-dimensional.

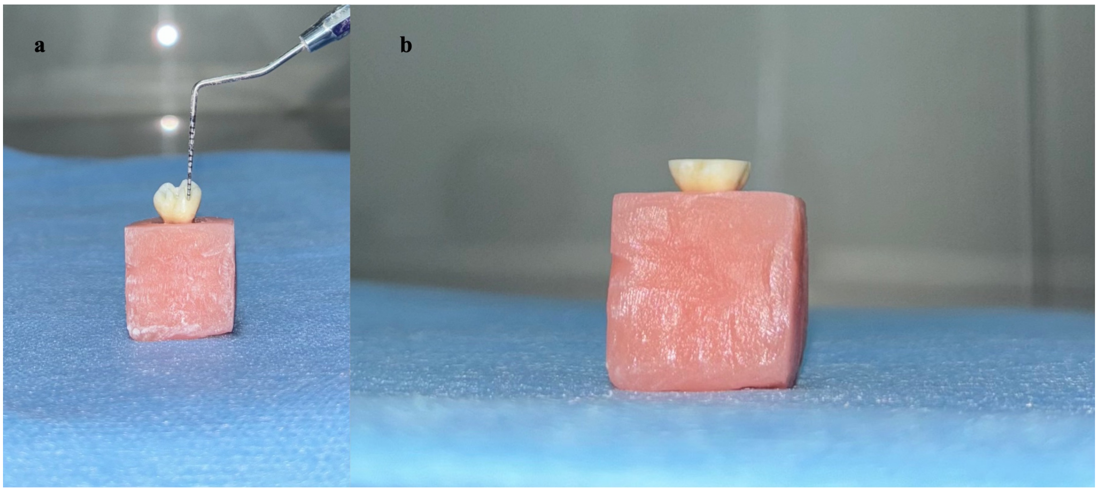


FIGURE 2. Standardized endocrown cavity preparation. (a) Preparation of 2 mm depth orientation grooves; (b) completion of occlusal reduction.

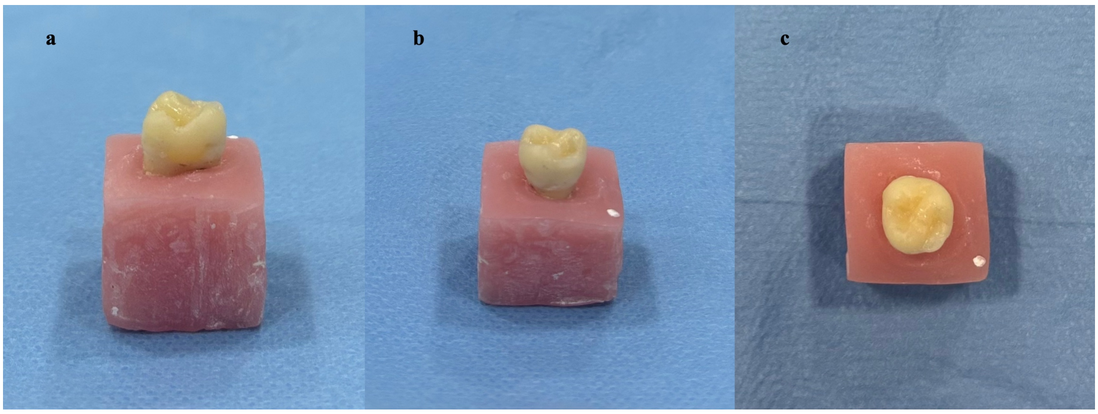


FIGURE 3. Direct composite (Essentia Universal, GC Corp., Tokyo, Japan) endocrown. (a) Mesial view of the direct composite endocrown restoration; (b) Palatinal view of the direct composite endocrown restoration; (c) Occlusal view of the direct composite endocrown restoration.

ability among groups.

Finishing and polishing were performed using a standardized OptraPol polishing system (Ivoclar Vivadent, Schaan, Liechtenstein) to ensure consistent surface characteristics.

2.6.2 Digitally fabricated endocrowns

For the digitally fabricated groups, restorations were designed and manufactured using a digital workflow. Digital impressions were obtained using an intraoral scanner (CEREC Omnicam, Sirona Dental Systems, Bensheim, HE, Germany) to simulate a clinically relevant digital workflow. The digital models were imported into CAD software (CEREC SW 5.2.10, Sirona Dental Systems, Bensheim, HE, Germany) for restoration design. A standardized workflow was applied to all specimens, including the administration, acquisition, modeling, design, and milling stages. Due to software limitations, the restoration type was defined as inlay/onlay, and the “Biogeneric Individual” design mode was selected for all restorations. To simulate primary molar morphology, permanent first molars (teeth 16 and 26) were used as reference models.

All specimens were prepared using the previously described standardized endocrown preparation protocol. The cement space was set to 50 μm, and occlusal morphology was automatically generated by the software and maintained across all specimens. To further standardize restoration thickness, the occlusal height measured from the central fossa was uniformly set at 3.5 mm for all specimens, corresponding to the loading point during fracture resistance testing. Together with standardized tooth selection and preparation, this approach ensured consistent restoration geometry across all groups, allowing differences in fracture resistance to be attributed primarily to material properties and fabrication techniques.

As regards the subtractive manufacturing groups, restorations were fabricated from prefabricated blocks using a CAD/CAM milling unit (CEREC MC XL, Sirona Dental Systems, Bensheim, HE, Germany) (Fig. 4). Millable resin-matrix ceramic blocks (Cerasmart 270, GC Corp., Tokyo, Japan) and millable composite blocks (Tetric CAD, Ivoclar Vivadent, Schaan, Liechtenstein) were used according to the respective experimental groups.

The milling process was performed using manufacturer-recommended burs, including a step bur for shaping the axial and internal surfaces and a cylinder-pointed bur for occlusal contouring. Milling was carried out under continuous water irrigation using the fine milling mode of the CAD/CAM system to enhance surface resolution and marginal accuracy.

For the additive manufacturing group, restorations were fabricated using a digital light processing (DLP)-based 3D printing system (3D-Printer, Varseo XS, BEGO, Bremen, HB, Germany) with a permanent crown resin material (VarseoSmile Crown Plus, BEGO, Bremen, HB, Germany) (Fig. 5). The designs generated in the CEREC software were exported as Standard Triangulation Language (STL) files and processed using the BEGO CAMcreator (v5.1.11, BEGO, Bremen, HB, Germany) software before printing. The restorations were printed layer-by-layer according to the manufacturer’s recommended parameters, with a layer thickness of 50 μm. All 3D printing procedures were performed by an experienced technician using a standardized workflow to minimize operator-related variability. Specimens were printed using the manufacturer’s recommended build orientation, and support structures were strategically positioned on the occlusal surfaces of the endocrowns to prevent interference with the internal fitting surfaces.

After printing, the restorations were cleaned using an ultrasonic cleaner (Ultrasonic Cleaner CD-4820, Codyson, Shenzhen, Guangdong, China) for 3 minutes, followed by the application of a 96% ethanol spray to remove residual resin. The specimens were then air-dried, and the support structures were carefully removed.

Subsequently, the restorations were post-cured for 30 minutes using a xenon light polymerization unit (Otoflash, BEGO, Bremen, HB, Germany) with a broad emission spectrum (approximately 300–700 nm) under protective gas conditions to ensure complete polymerization and reduce residual monomer content.

Finishing and polishing procedures were performed using a standardized OptraPol polishing system (Ivoclar Vivadent, Schaan, Liechtenstein) at low speed under light pressure according to the manufacturer’s instructions to ensure consistent surface characteristics across all specimens. Finally, all digitally fabricated restorations were stored at room temperature, protected from light, until cementation.

2.7 Cementation protocol

All restorations were cemented using a dual-cure resin cement (G-CEM ONE, GC Corp., Tokyo, Japan) and polymerized with an LED light-curing unit (D-Light Duo, GC Corp., Tokyo, Japan) with an output intensity of approximately 1200 mW/cm^2. Surface treatment protocols were selected according to the manufacturers’ recommendations for each material.

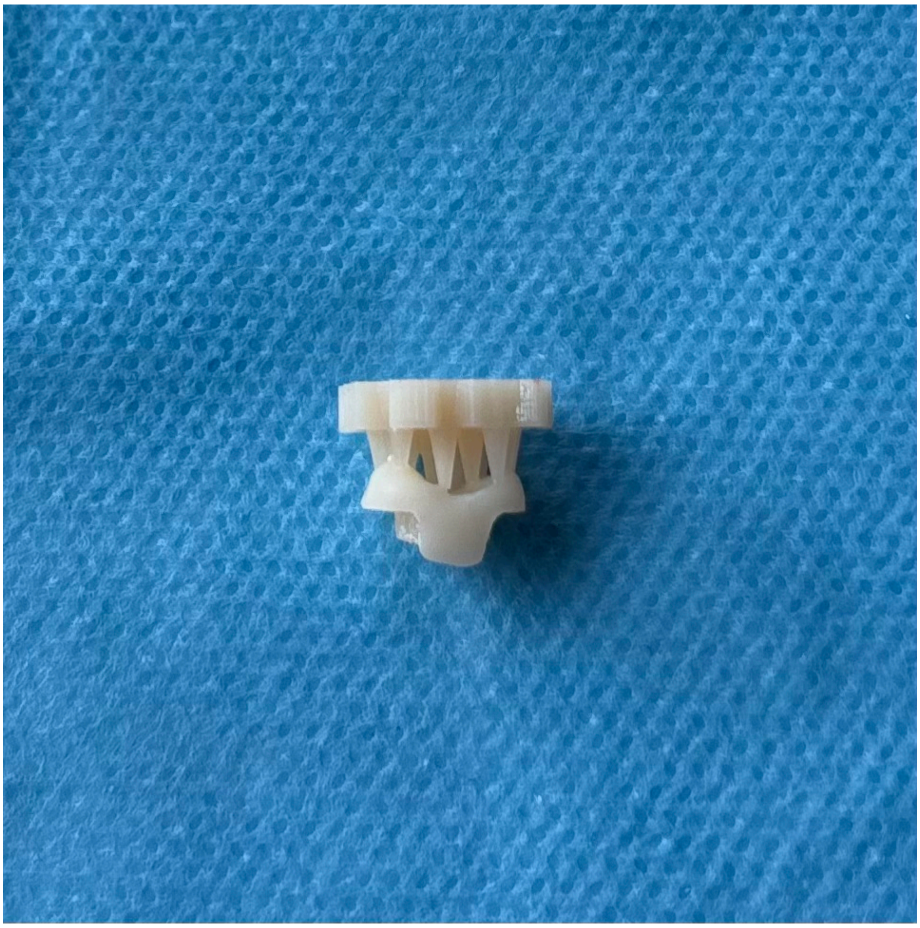
Hydrofluoric acid etching has been widely reported as an effective surface treatment for resin-matrix ceramics, enhancing micromechanical retention and bond strength [37]. For the milled resin-matrix ceramic group, the intaglio surfaces of the restorations were etched with 5% hydrofluoric acid for 60 seconds, rinsed thoroughly with water for 60 seconds, and air-dried. Afterwards, a ceramic primer (G-Multi PRIMER, GC Corp., Tokyo, Japan) was applied using a microbrush and allowed to dry for 60 seconds.

For the milled composite group, the intaglio surfaces were treated with air abrasion using 50 μm aluminum oxide particles (Korox, BEGO, Germany) at 1.5 bar pressure from a distance of 10 mm for 15 seconds. The restorations were then cleaned with a 70% ethanol spray, rinsed with an air–water spray, and gently air-dried. Subsequently, a single coat of universal adhesive (G-Premio Bond, GC Corp., Tokyo, Japan) was applied without light-curing.

For the 3D-printed resin group, the intaglio surfaces were treated with air abrasion using 50 μm aluminum oxide particles (Korox, BEGO, Germany) at 2 bar pressure from a distance of 10 mm for 10 seconds to enhance micromechanical retention.

For all specimens, the enamel surfaces were selectively etched with 37% phosphoric acid (GC ETCHANT, GC Corp., Tokyo, Japan) for 30 seconds, followed by thorough rinsing with water spray for 30 seconds and gentle air-drying for an additional 30 seconds. Next, a single coat of universal adhesive

F I G U R E 4. Completed CAD-CAM milled restoration.



F I G U R E 5. 3D-printed restoration before removal from the supporting structures.

(G-Premio Bond, GC Corp., Tokyo, Japan) was applied using a microbrush, gently air-thinned to remove excess solvent, and light-cured for 40 seconds.

Further, resin cement was applied to both the intaglio surfaces of the restorations and the prepared tooth surfaces. The restorations were seated under consistent finger pressure, followed by a 2-second initial light-curing. Excess cement was carefully removed with a scaler, and final light-curing was performed from all aspects for 20 seconds each. The cementation procedure was completed by allowing the cement to set for 5 minutes (Figs. 6,7,8).

2.8 Fracture resistance testing and failure mode assessment

All specimens were subjected to fracture resistance testing using a universal testing machine (Autograph AG-X, Shimadzu Corporation, Kyoto, Japan) equipped with a 5 kN load cell. Each specimen was mounted in the testing device and loaded using a stainless-steel spherical tip with a diameter of 4 mm. The load was applied vertically to the central fossa of each tooth, parallel to its long axis, at a crosshead speed of 1 mm/min until fracture occurred (Fig. 9). The fracture load was recorded in Newtons (N). The point of fracture was identified by a sudden drop in the load–displacement curve and confirmed by an audible crack.

After fracture testing, all specimens were examined under a stereomicroscope (stereomicroscope, Leica Microsystems, Wetzlar, HE, Germany) at ×10 magnification. This magnification level was selected to provide sufficient detail for reliable fracture pattern evaluation, which is consistent with a previous *in vitro* study [38]. Failure modes were classified according to the criteria described by Burke into five categories (Type I–V) [39], as shown in Table 2. Moreover, all evaluations were performed by the same operator under blinded conditions.

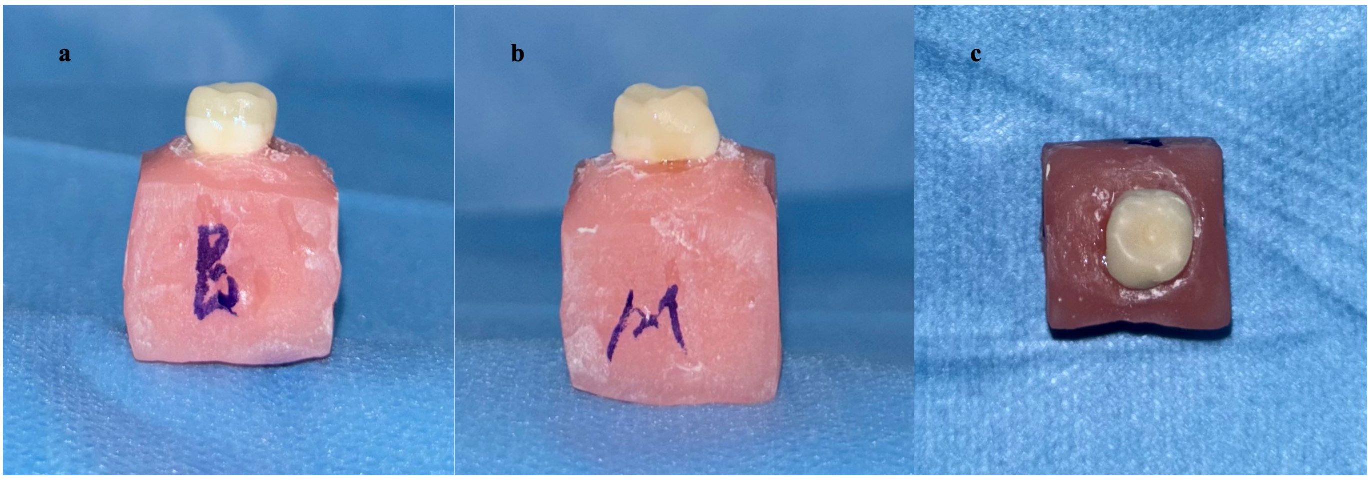


FIGURE 6. Milled resin-matrix ceramic (Cerasmart 270, GC Corp., Tokyo, Japan) endocrown restoration after adhesive cementation. (a) Buccal view of the milled resin-matrix ceramic endocrown restoration; (b) Mesial view of the milled resin-matrix ceramic endocrown restoration; (c) Occlusal view of the milled resin-matrix ceramic endocrown restoration.

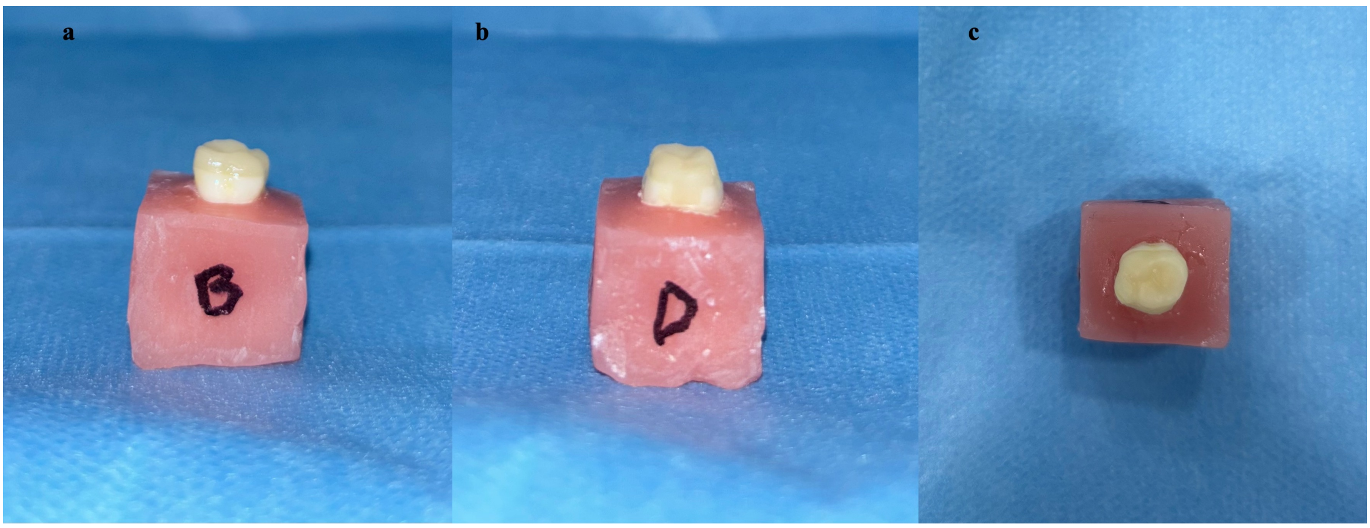


FIGURE 7. Milled composite Tetric CAD (Ivoclar Vivadent, Schaan, Liechtenstein) endocrown restoration after adhesive cementation. (a) Buccal view of the milled composite endocrown restoration; (b) Distal view of the milled composite endocrown restoration; (c) Occlusal view of the milled composite endocrown restoration.

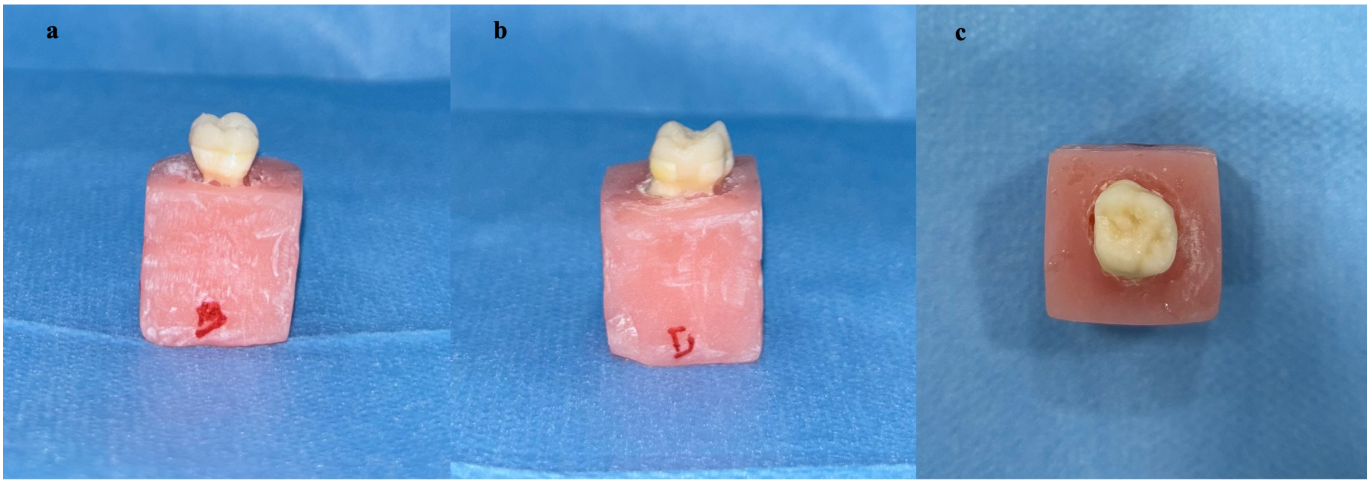


FIGURE 8. 3D-printed resin (VarseoSmile Crown Plus, BEGO, Bremen, HB, Germany) endocrown restoration after adhesive cementation. (a) Buccal view of the 3D-printed resin endocrown restoration. (b) Distal view of the 3D-printed resin endocrown restoration. (c) Occlusal view of the 3D-printed resin endocrown restoration.

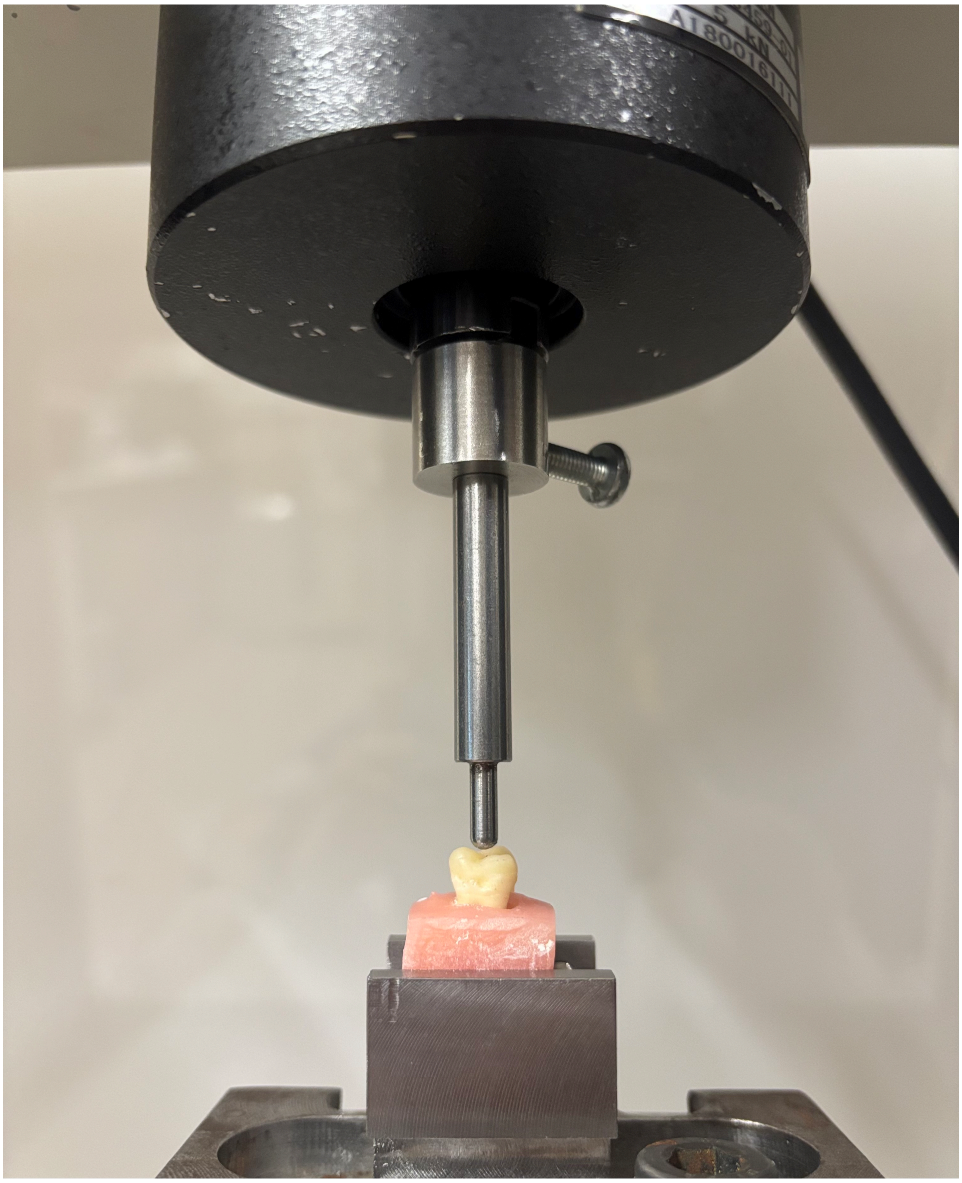


FIGURE 9. Fracture resistance testing setup using a universal testing machine.

TABLE 2. Classification of failure modes.

Type	Description
Type I	Minimal crack
Type II	Loss of <50% of the crown
Type III	Loss of 50% of the crown
Type IV	Loss of >50% of the crown
Type V	Severe tooth or crown fracture

2.9 Statistical analysis

Statistical analyses were performed using the IBM SPSS Statistics software (Version 22.0, IBM Corp., Armonk, NY, USA). The normality of data distribution was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. As the fracture resistance data revealed normal distribution, one-way analysis of variance (ANOVA) was performed to compare fracture resistance values among the groups, followed by Tukey's Honest Significance Difference (HSD) *post hoc* test. Failure mode data, being categorical variables, were analyzed using the chi-square test.

3. Results

3.1 Fracture resistance analysis

The fracture resistance values of the experimental groups are summarized in Table 3 and illustrated in Fig. 10. Fracture resistance values ranged from 718.9 N to 2056.3 N. The highest mean fracture resistance was observed in the milled resin-matrix ceramic group (1572.42 ± 265.67 N), followed by the milled composite group (1494.00 ± 360.85 N), the direct composite group (1211.09 ± 300.76 N), and the 3D-printed resin group (1068.14 ± 199.67 N).

A statistically significant difference was found among the groups (one-way ANOVA, p = 0.001). *Post hoc* Tukey's HSD analysis revealed that the milled resin-matrix ceramic group demonstrated significantly higher fracture resistance than the direct composite (p = 0.038) and 3D-printed resin groups (p = 0.002). Additionally, the milled composite group demonstrated significantly higher fracture resistance than the 3D-printed resin group (p = 0.011). No statistically significant differences were observed among the remaining comparisons (Table 4).

3.2 Failure mode analysis

No statistically significant differences were observed among the groups (chi-square test, p = 0.630). Type V fractures were the most frequently observed failure pattern in all groups. The distribution of failure modes is presented in Table 5 and Fig. 11, while the examples of failure types for experimental groups are shown in Fig. 12.

4. Discussion

The restoration of pulpotomized primary molars continues to pose a clinical challenge due to the extensive loss of tooth structure and increased susceptibility to fracture following pulp therapy [40]. In recent years, endocrown restorations have garnered attention as a conservative treatment option that allows for the preservation of tooth structure while utilizing the pulp chamber for retention [17]. With the increasing use of digital technologies, CAD/CAM and 3D-printed restorations have emerged as alternative approaches in pediatric restorative dentistry.

Previous studies have evaluated the fracture resistance of various restorative options for primary molars, including prefabricated crowns and CAD/CAM-fabricated restorations. For instance, studies by Ali *et al.* [34] and El Makawi and Khattab demonstrated that endocrowns fabricated using CAD/CAM systems show clinically acceptable fracture resistance values in pulpotomized primary molars [35]. Similarly, Yehia *et al.* [36] reported no statistically significant differences among different CAD/CAM endocrown materials, suggesting that multiple materials may provide comparable mechanical performance. However, these studies primarily focused on restorations produced using subtractive manufacturing techniques. To the best of our knowledge, there is limited evidence that directly compares endocrowns fabricated using both subtractive and additive manufacturing techniques in primary molars.

Although glass ceramics, such as lithium disilicate, have been widely used in previous studies in primary teeth, their higher elastic modulus and brittle behavior may lead to less favorable stress distribution and an increased risk of catastrophic failure [34, 35]. Accordingly, El-Damanhoury *et al.* [41] reported that resin-matrix ceramic endocrowns demonstrated higher fracture resistance and more favorable failure patterns than glass ceramics, whereas Pedrollo Lise *et al.* [42] showed that resin-based endocrowns may perform more favorably than lithium disilicate materials, particularly in deeper cavity designs. Therefore, the present study focused exclusively on resin-based materials to evaluate the effect of fabrication technique while minimizing the influence of brittle ceramic materials.

Different loading tip diameters have been reported in previous fracture resistance studies in primary molars. For instance, Ali *et al.* [34] used a 5.8 mm diameter stainless-steel tip for endocrowns in mandibular primary molars, whereas Şimşek and Derelioğlu used a 3.6 mm diameter tip for inlay restorations in maxillary primary molars [43]. Although these studies investigated different restoration types, they indicate that loading tip dimensions are often adapted according to tooth size and restoration type. In the present study, endocrowns in maxillary second primary molars were evaluated, which are smaller than mandibular primary molars. Therefore, a 4 mm diameter loading tip was selected to provide appropriate occlusal contact and ensure controlled stress distribution during loading.

The results of this study revealed that milled resin-matrix ceramic materials exhibited the highest fracture resistance values, followed by milled composite materials. Meanwhile, direct composite endocrowns and 3D-printed resin showed lower values. These findings are consistent with those of previous studies, which reported that indirect and CAD/CAM-fabricated restorations exhibit superior mechanical performance compared with direct composite restorations. For example, Papadopoulos *et al.* [44] reported that CAD/CAM composite restorations provide

TABLE 3. Fracture resistance values (N) of the experimental groups (mean ± SD).

Group (Material)	Mean ± SD	Min–Max
Group 1—Direct Composite Resin	$1211.09 \pm 300.76^{a,c}$	795.5–1673.6
Group 2—Milled Resin-Matrix Ceramic	1572.42 ± 265.67^{b}	1198.9–1913.1
Group 3—Milled Composite	$1494.00 \pm 360.85^{b,c}$	1062.8–2056.3
Group 4—3D-Printed Resin	1068.14 ± 199.67^{a}	718.9–1296.3

$p = 0.001$ (One-way ANOVA). Groups sharing at least one common superscript letter are not significantly different from each other, whereas groups with different superscript letters are significantly different (Tukey's HSD, $p < 0.05$). SD: Standard deviation; Min: Minimum; Max: Maximum.

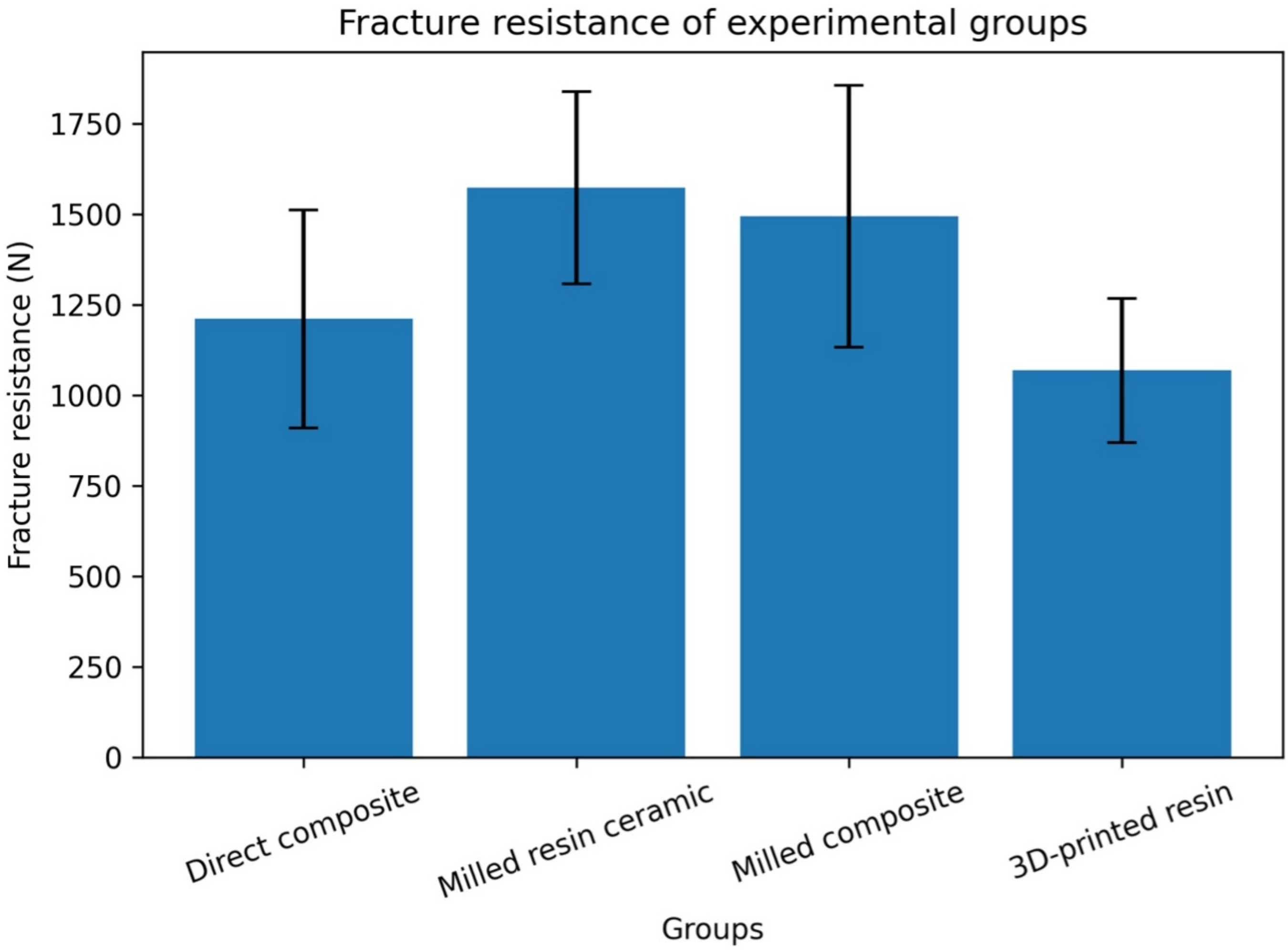


FIGURE 10. Mean fracture resistance values (N) of the experimental groups: error bars represent standard deviation.

TABLE 4. Pairwise comparisons of fracture resistance (Tukey's HSD test).

Comparison	*p*-value
Direct Composite Resin *vs.* Milled Resin-Matrix Ceramic	0.038*
Direct Composite Resin *vs.* Milled Composite	0.143
Direct Composite Resin *vs.* 3D-Printed Resin	0.685
Milled Resin-Matrix Ceramic *vs.* Milled Composite	0.928
Milled Resin-Matrix Ceramic *vs.* 3D-Printed Resin	0.002*
Milled Composite *vs.* 3D-Printed Resin	0.011*

*$p < 0.05$.

TABLE 5. Distribution of failure modes (n, %).

Failure Type	Direct Composite Resin n (%)	Milled Resin-Matrix Ceramic n (%)	Milled Composite n (%)	3D-Printed Resin n (%)
Type I	2 (20%)	0 (0%)	3 (30%)	4 (40%)
Type II	2 (20%)	2 (20%)	1 (10%)	2 (20%)
Type III	0 (0%)	1 (10%)	0 (0%)	0 (0%)
Type IV	1 (10%)	1 (10%)	0 (0%)	0 (0%)
Type V	5 (50%)	6 (60%)	6 (60%)	4 (40%)

p = 0.630 (Chi-square test).

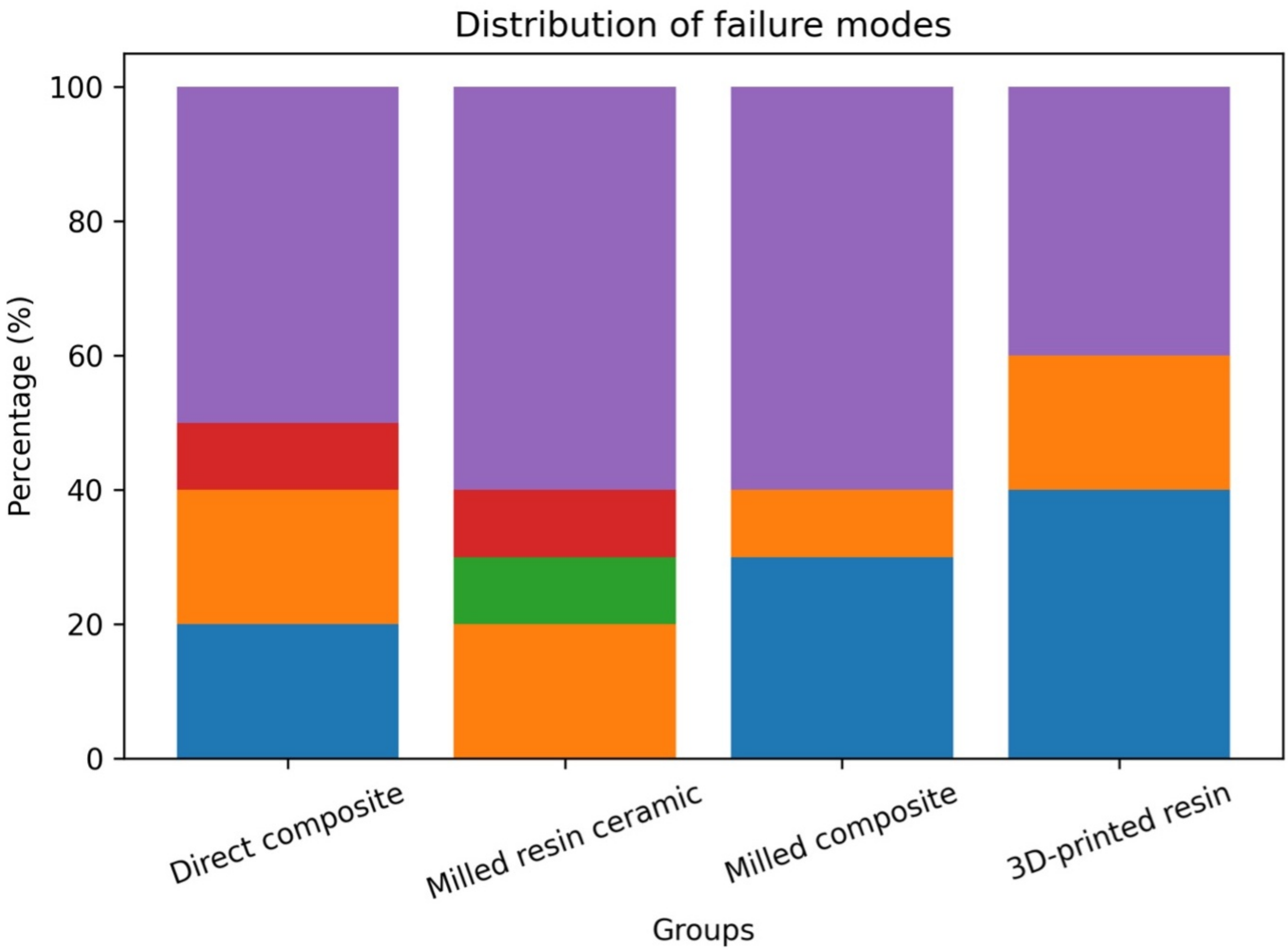


FIGURE 11. Distribution of failure modes among the experimental groups.

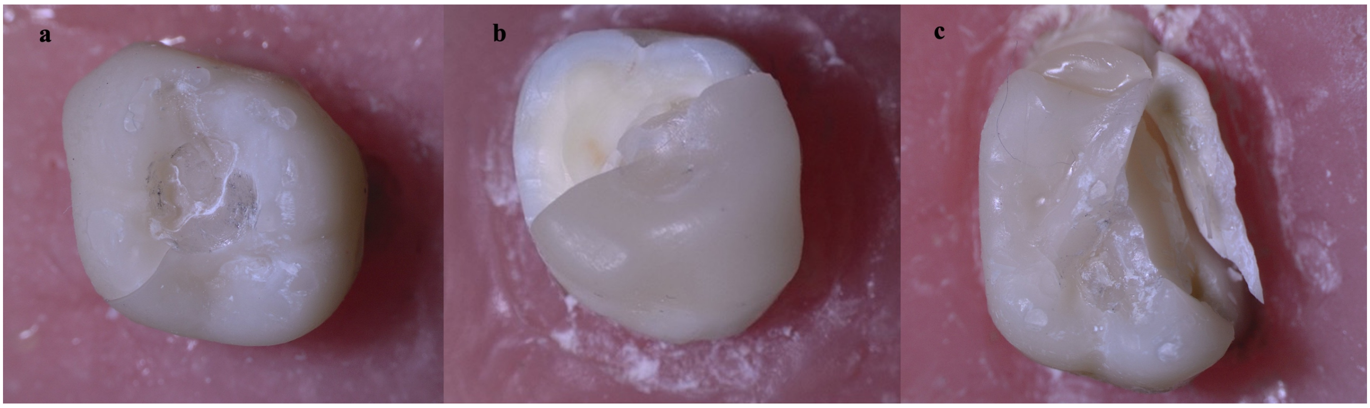


FIGURE 12. Examples of failure types for experimental groups. (a) Type I failure; (b) Type III failure; (c) Type V failure.

greater structural integrity than directly applied composites. Similarly, Tsertsidou *et al.* [45] demonstrated that CAD/CAM restorations show significantly higher fracture resistance compared with direct composite restorations in large cavity designs. As for primary teeth, Simsek and Derelioglu also reported that indirect and CAD/CAM restorations exhibit higher fracture resistance than direct composite restorations [43].

In the present study, the direct group comprised direct composite endocrowns prepared using a standardized endocrown cavity design rather than conventional intracoronal restorations. Despite the advantages of endocrown geometry, this group demonstrated lower fracture resistance, indicating that cavity design alone is not sufficient to compensate for the inherent limitations of direct composite materials. Polymerization shrinkage, incomplete monomer conversion, and internal stress formation may negatively affect the mechanical performance of direct restorations [46].

Regarding material composition, the superior performance of the resin-matrix ceramic group in the present study is consistent with previous findings. For instance, Mertsöz *et al.* [47] reported that resin-matrix ceramic endocrowns exhibit high fracture resistance and favorable mechanical behavior. Resin-based CAD/CAM materials benefit from a homogeneous microstructure and an elastic modulus closer to dentin, which may allow for more favorable stress distribution [48, 49].

The lower fracture resistance observed in the 3D-printed resin group may be explained by differences in manufacturing technology and material structure. Notably, CAD/CAM materials are produced under industrial conditions involving high temperature, pressure, and controlled polymerization, resulting in a highly homogeneous structure with low porosity, high monomer conversion, and strong filler–matrix bonding [50, 51]. These characteristics contribute to their superior mechanical properties. Conversely, 3D printing is based on an additive manufacturing process in which the material is polymerized layer by layer, potentially resulting in a less homogeneous structure, with potential interlayer defects, microvoids, and variations in polymerization depth. Additionally, the absence of high-pressure and high-temperature polymerization may limit cross-linking density and bonding strength within the material [52, 53]. These factors can negatively affect the internal integrity and mechanical performance of 3D-printed restorations, leading to lower fracture resistance values. This suggests that the manufacturing technique may significantly influence fracture resistance and that 3D-printed restorations generally exhibit lower mechanical performance compared with milled restorations.

Nevertheless, Aktaş and Bankoğlu Güngör reported no significant differences in fracture resistance among 3D-printed resin, milled resin-matrix ceramic, and milled composite crown restorations [54]. This discrepancy may be attributed to differences in study design, considering that their study utilized 3D-printed resin tooth models instead of extracted natural teeth and evaluated full-coverage crown restorations rather than endocrowns. These factors may have influenced the mechanical behavior and fracture resistance outcomes.

Although no statistically significant differences were observed in failure mode distribution among the groups, the distribution of failure modes demonstrated certain trends that may be clinically relevant, particularly in terms of repairability. Failures confined to the restoration may be regarded as more favorable, as they are potentially repairable, whereas fractures involving extensive tooth structure, particularly in the cervical or root regions, are generally considered catastrophic and may lead to extraction.

Severe fracture patterns (Type V), involving extensive destruction of the restoration and/or tooth structure, were the most frequently observed failures in all groups, particularly in the milled resin-matrix ceramic and milled composite groups (60%). These findings suggest that materials with higher fracture resistance may withstand greater loads before failure; however, when failure occurs, it tends to be more catastrophic and potentially non-repairable. Conversely, the 3D-printed resin group exhibited a higher proportion of more favorable failure modes, with Type I fractures (minimal cracks) being the most common (40%). These less destructive failure patterns may indicate a greater capacity for deformation before fracture and suggest a higher likelihood of repairability in clinical scenarios.

From a clinical perspective, all tested materials demonstrated fracture resistance values exceeding the average masticatory forces reported in children, which generally range between approximately 100 and 430 N during the mixed dentition period [55–57]. However, it should be noted that fracture resistance values obtained under static loading do not necessarily reflect long-term clinical performance under cyclic fatigue and complex intraoral conditions.

Despite the promising mechanical performance of digitally fabricated endocrowns, stainless steel crowns remain the gold standard for restoring pulpotomized primary molars due to their well-documented clinical success and reduced technique sensitivity. In contrast, adhesive endocrowns require adequate isolation and reliable bonding, which may be challenging in pediatric patients [3]. Bonding to primary teeth presents additional challenges due to differences in enamel and dentin composition, including lower mineral content and larger dentinal tubules [19]. These factors, combined with difficulties in moisture control, may negatively affect adhesion and increase the risk of debonding as a potential clinical failure mode.

Some limitations of this study are its *in vitro* design, the absence of thermocycling and mechanical aging, the lack of periodontal ligament simulation, and the evaluation being only under static loading conditions. These factors limit the ability to simulate long-term intraoral degradation and complex biomechanical conditions. In addition, the absence of periodontal ligament simulation and the use of static, purely vertical loading may affect stress distribution and fracture behavior. Considering that masticatory forces in primary molars are typically oblique and dynamic, the clinical relevance of the present loading conditions may be limited. Therefore, further *in vitro* studies incorporating aging protocols, as well as long-term clinical studies, are required to validate these findings.

5. Conclusions

Within the limitations of this *in vitro* study, both material type and fabrication technique influenced the fracture resistance of endocrown restorations, with milled resin-matrix ceramic showing the highest values. Although all evaluated materials exceeded reported masticatory forces in children, these findings should be interpreted with caution, as fracture resistance alone cannot fully predict clinical success. Thus, further long-term *in vitro* and clinical studies are required to validate these findings.

AVAILABILITY OF DATA AND MATERIALS

The data underlying the results of this study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

IY and KG—contributed to the conception and design of the study. IY—carried out the experimental procedures, collected the data, and prepared the first draft of the manuscript. BMB—contributed to the statistical analysis, data interpretation, and methodological evaluation of the study. MK—contributed to data interpretation and critically reviewed the study findings. All authors reviewed the results, contributed to the revision of the manuscript, critically reviewed the manuscript for important intellectual content, and approved the final version.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This *in vitro* study was approved by the Clinical Research Ethics Committee of Istanbul University Faculty of Dentistry (Approval No: 2023/49; 07 December 2023). Extracted human maxillary second primary molars were obtained with informed consent from the patients' legal guardians. The study was conducted in accordance with the principles of the Declaration of Helsinki.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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