Mechanical Evaluations of Devitalized Teeth Reconstructed Using Direct and Indirect Techniques

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Abstract

1.Background/Objectives: This study evaluates the efficiency of direct and indirect corono-radicular reconstruction techniques for devitalized teeth, focusing on mechanical resistance, aesthetic outcomes, and cost-effectiveness. *2.Methods:* Two groups of extracted human teeth, previously endodontically treated, were restored using direct (fiberglass posts and composite resin) and indirect (zirconia-based) methods. Compression resistance tests were performed using a Zwick/Roell ProLine Z005 universal testing machine following ISO 7500-1 standards. Maximum force (F_{max}) and displacement at failure (Δl_{max}) were recorded, and compressive stress (S_{max}) was calculated by normalizing force with cross-sectional preparation area measured via radiographic analysis including CBCT. *3.Results:* Zirconia restorations exhibited significantly higher compressive strength (average S_{max} = 30.63 MPa) compared to fiberglass restorations (average S_{max} = 20.33 MPa). Fiberglass-based samples showed greater elasticity with lower displacement at failure. Both materials provided satisfactory initial aesthetics, though composite resin showed slight discoloration over time. Direct restorations were more cost-effective and time-efficient, while zirconia offered superior long-term durability. CBCT evaluation confirmed precise adaptation and placement of restorations. *4.Conclusion:* Direct techniques are effective for moderate-load applications due to affordability and flexibility, whereas indirect zirconia restorations are preferable for high-stress scenarios requiring enhanced mechanical resistance. Further studies should focus on optimizing material properties for improved longevity and aesthetic stability.

Keywords: corono-radicular reconstruction, devitalized teeth, direct technique, zirconia, fiberglass, mechanical resistance, aesthetic outcomes, cost effectiveness

INTRODUCTION

Restoring endodontically treated teeth remains a key challenge in dentistry, requiring both aesthetics and long-term functional stability [1,2]. Corono-radicular reconstruction plays a crucial role in preserving these teeth, preventing fractures, and restoring occlusal function [3]. The selection of an appropriate reconstruction technique depends on multiple factors, including the extent of structural loss, material properties, patient preferences, and cost considerations [4].

Two primary approaches are widely used in corono-radicular restorations: direct techniques and indirect techniques. Direct techniques involve the immediate reconstruction of the tooth structure using composite resins and prefabricated fiberglass posts, performed chairside by the clinician [5]. These methods offer advantages such as reduced treatment time, lower costs, and preservation of more dental tissue. Nevertheless, these restorations may present certain drawbacks, such as reduced fracture resistance and an increased chance of marginal leakage as time passes [6,7].

In contrast, indirect techniques involve the fabrication of custom-made restorations, such as zirconia or metal-based DCRs, in a dental laboratory [8]. These restorations are recognized for their excellent mechanical strength and greater resistance to fractures, yet they involve several clinical appointments, higher lab expenses, and more complicated cementation procedures [9,10]. While indirect restorations provide long-term benefits, their cost and procedural complexity often make them less accessible to patients [11].

Advancements in adhesive dentistry and biomaterials have significantly improved the clinical outcomes of both techniques [12]. Contemporary bonding agents and resin cements improve the adhesion of direct restorations, thereby increasing their durability [13]. At the same time, CAD/CAM technologies allow for highly precise fabrication of indirect restorations, optimizing their fit and resistance [14]. Despite these technological advancements, the ideal reconstruction technique remains a subject of debate, requiring further comparative studies to determine the most effective approach based on clinical performance, durability, and cost-effectiveness [15,16].

Aim and objectives

The primary objective of this study is to evaluate and compare the effectiveness of direct and indirect corono-radicular reconstruction techniques in devitalized teeth. The aim of the study is to perform an ex-vivo comparison on extracted human teeth with different morphologies (pulpal morphology, root canals), which, after endodontic treatment, were restored using direct and indirect techniques. The behavior of the samples was compared under mechanical stress.

Additionally, a fractographic analysis of the ex vivo tested samples will be conducted to identify fracture patterns and evaluate the structural behavior of the materials used. The study also seeks to assess the aesthetic performance of both techniques over time, focusing on factors such as color stability and translucency. Finally, a cost-effectiveness and procedural efficiency evaluation will be carried out, considering both short-term and long-term clinical implications.

By providing a comprehensive comparison of these techniques, the study seeks to offer evidence-based recommendations that can guide clinicians in selecting the most appropriate restorative approach based on individual patient needs and clinical scenarios.

MATERIAL AND METHODS

This primary ex vivo study was conducted using two groups of specimens, each consisting of four extracted human teeth that had undergone prior endodontic treatment. The selection criteria included teeth with intact roots, no significant fractures, and comparable anatomical dimensions to ensure consistency in the experimental conditions. A total of eight extracted human teeth with varying root and crown morphologies were selected for this study, as shown in Figure 1.

Figure 1. Extracted human teeth used in the study, divided into two experimental groups based on the restorative technique

Initially, all specimens were subjected to a standardized mechanical and chemical cleaning protocol, followed by obturation with gutta-percha cones at the established working length in combination with a root canal sealer (Root Canal Sealer ADSEAL MetaBiomed). The purpose of this step was to ensure optimal sealing of the root canal system before proceeding with corono-radicular reconstruction.

For the first group (S1, S2, S3, S4), a direct technique was employed using glass fiber posts (Nordin Glassix Radiopaque Glass Fiber Post), which were cemented within the root canal using a self-adhesive dual-cure resin cement (G-CEM One). The coronal portion of the tooth was then restored with a light-curing composite resin (RDC 3M ESPE Valux Plus). This approach aimed to evaluate the efficiency and adhesive properties of direct restorative materials, as well as their adaptation to the root canals and coronal structure. The fiberglass-reinforced direct restorations used in the study are illustrated in Figure 2, showing occlusal or incisal views of samples S1 to S4.

Figure 2. Occlusal and incisal views of the teeth restored using direct technique with fiberglass posts and composite resin. The samples were embedded in acrylic resin cylinders, labeled to identify their anatomical origin (S1–S4): a) S1 – inferior premo

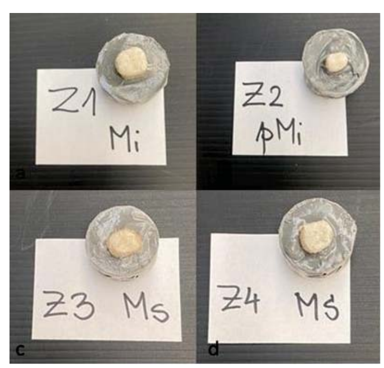

Figure 3. Occlusal views of teeth restored using the indirect technique with zirconia post-and-core systems. The samples (Z1–Z4) are embedded in acrylic resin blocks and correspond to various tooth types: a) Z1 – inferior molar, b) Z2 – inferior premolar, c) Z3 – superior molar, d) Z4 – superior molar

For the second group (Z1, Z2, Z3, Z4), an indirect technique was applied, utilizing zirconia-based corono-radicular restorations (CRRs). These restorations were fabricated through a digital workflow, which included scanning the prepared tooth models, followed by milling and sintering. The final restorations were cemented into the root canals using a universal dual-cure resin cement (Maxcem Elite Kerr). The primary objective of this technique was to assess the mechanical strength, durability, and resistance of zirconia restorations under masticatory stress conditions. The indirect restorations using zirconia posts and cores are shown in Figure 3, with occlusal views of samples Z1 to Z4.

Before conducting mechanical tests and fractographic evaluations, all samples were subjected to imaging analysis to examine the restorations and internal structure of the teeth. For each sample, both 2D retroalveolar radiographs were taken using an intraoral X-ray device (Planmeca ProX), and cone-beam computed tomography (CBCT) scans were performed with the Planmeca ProMax 3D Classic, allowing for a three-dimensional assessment. The CBCT analysis provided detailed visualization of the samples in three planes: coronal, sagittal, and axial, offering additional insights into the positioning and adaptation of the restorations. All radiographic evaluations were performed using the Planmeca ProX unit (Figure 4), allowing for consistent alignment and standardized imaging across all samples and CBCT imaging was performed using the Planmeca ProMax 3D Classic system (Figure 5), which enabled high-resolution 3D scans of the radicular structures and precise evaluation of material adaptation. Retroalveolar radiographs were taken for all samples to verify the position and integrity of the restorations within the root structure (Figure 6). These images provided comparative visual confirmation of material adaptation and post placement in both zirconia and fiberglass groups. Prior to the CAD/CAM workflow, all samples were visually inspected and photographed from multiple angles to document their morphology and preparation status (Figure 7). To evaluate the internal adaptation of the restorative materials and the structural integrity of the roots, CBCT scans were analyzed across three anatomical planes: coronal, sagittal, and axial (Figure 8). These images ensured proper orientation during the subsequent 3D scanning procedure. The resistance of the samples was calculated considering the diameter and length of the reconstructions. For stabilization during scanning, the teeth were fixed in a custom support made of condensation-cured silicone impression material. Each sample was oriented according to its natural anatomical position in the oral cavity, based on the experimental group to which it belonged. This step ensured the accuracy and reproducibility of the measurements, as well as proper alignment during imaging analyses and subsequent testing.

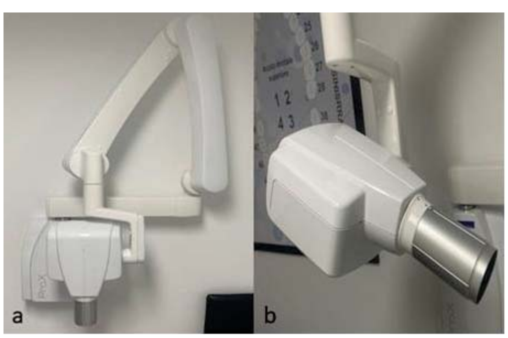

Figure 4. Extraoral radiographic device (Planmeca ProX) used for CBCT imaging. a) Frontal view showing the structural design and positioning arm; b) Lateral view illustrating the alignment and tube head orientation used during imaging of the samples

Figure 5. Cone-beam computed tomography (CBCT) system used for sample imaging: Planmeca ProMax 3D Classic. a) Lateral view illustrating the CBCT unit and patient positioning arm; b) Control display interface used for parameter adjustments and image acquisition monitoring

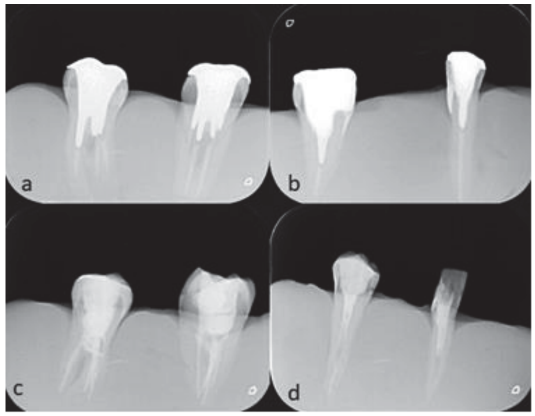

Figure 6. Retroalveolar radiographic images of the experimental tooth groups. a) Multi-rooted teeth restored with zirconia-based restorations; b) Single-rooted teeth restored with zirconia-based restorations; c) Multi-rooted teeth restored with fiberglas

Figure 7. Visualization of the two experimental tooth groups prior to 3D scanning. a) Occlusal (superior) view; b) Frontal view; c) Oblique view; d) Lateral view

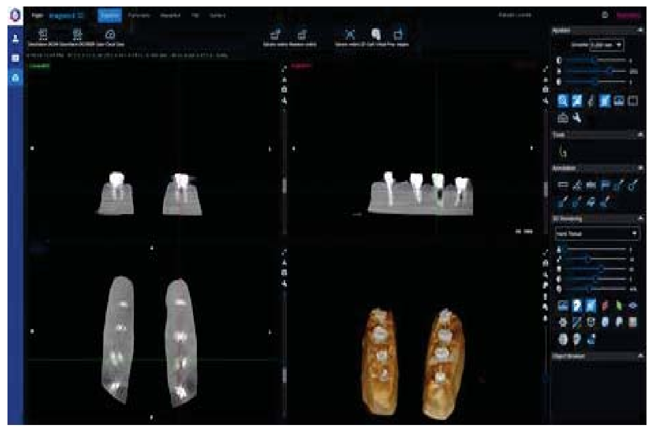

Figure 8. CBCT imaging planes used for sample evaluation: a) Coronal section; b) Sagittal section; c) Axial section

To evaluate the clinic performance of both techniques, the specimens underwent mechanical resistance testing, simulating masticatory forces under controlled conditions. Following mechanical testing, a fractographic analysis of the results was conducted using the universal testing machine at the Politehnica University of Timișoara (Zwick/Roell ProLineZ005). The goal was to examine the fracture surfaces and identify fracture patterns, providing insights into the structural behavior of the materials under stress. These observations are crucial for understanding the clinical implications and guiding restorative choices in dental practice. Additionally, digital microscopy was used to analyze the adaptation of the restorations to the root canal walls and the presence of microgaps at the interface.

The sample size used in this study was limited to four specimens per group due to the difficulty in obtaining extracted human teeth with similar anatomical characteristics and comparable endodontic conditions. While this relatively small sample size restricts the statistical power and generalizability of the findings, it is consistent with prior ex vivo studies that aim to establish preliminary mechanical and structural performance trends. This limitation is acknowledged and highlights the need for further research involving a larger cohort of specimens to confirm and expand upon the current results. Nevertheless, the experimental protocol was rigorously standardized, and CBCT analysis ensured consistent internal morphology and adaptation across samples, thereby strengthening the internal validity of the study.

Each sample was carefully positioned in the universal testing machine to ensure consistent loading conditions (Figure 9). The fiberglass-reinforced composite group (S1–S4) and the zirconia group (Z1–Z4) were subjected to uniaxial compressive force until failure.

Figure 9. Positioning of samples from both groups - S (fiberglass-reinforced composite) and Z (zirconia-based) - in the universal testing machine prior to mechanical testing: a) S1, b) S2, c) S3, d) S4, e) Z1, f) Z2, g) Z3, h) Z4

RESULTS

This study aimed to identify potential differences in fracture patterns between single-rooted and multi-rooted teeth, both in the upper and lower arches. Several key parameters that could influence the occurrence and type of fractures were analyzed, including the direction and point of force application, force intensity, root canal diameter, number of root canals, and the material used for the DCR. The load–displacement curve of sample S1 (Scheme I) reveals a steady increase in compressive force up to approximately 1000 N, followed by a sharp fluctuation, suggesting the onset of structural failure. The load–displacement curve of sample S2 (Scheme II) shows a progressive rise in compressive force reaching just under 2000 N, followed by slight oscillations, which may indicate microfractures before complete failure.

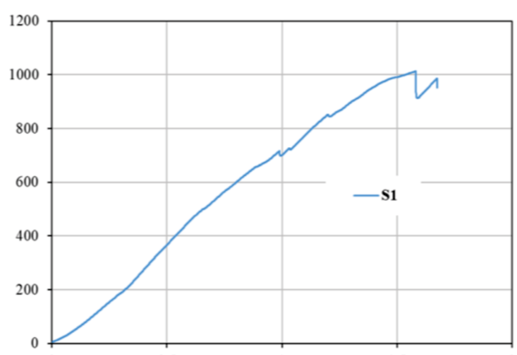

Figure 10. Force–displacement curve of sample S1 (fiberglass group), illustrating the mechanical response under compressive loading

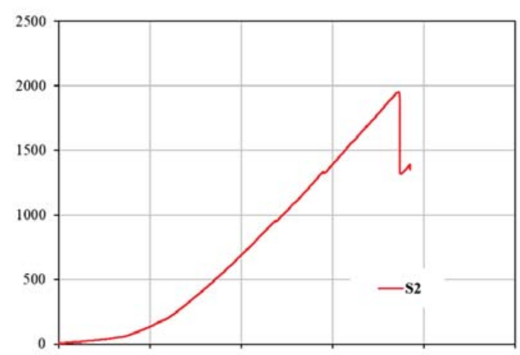

Figure 11. Force–displacement curve of sample S2 (fiberglass group), illustrating the mechanical response under compressive loading

Another crucial aspect considered was the alignment of upper and lower teeth. The maxillary arch circumscribes the mandibular arch, which results in an eccentric force application on the palatal surface of anterior maxillary teeth during normal occlusion. Consequently, maxillary anterior teeth are more susceptible to vertical coronal fractures. In contrast, multi-rooted teeth located in the lateral regions of the dental arches are more prone to horizontal fractures when restored with DCRs. The load–displacement curve of sample S3 (Scheme III) displays a consistent load increase up to around 1000 N, with a smoother decline, suggesting a more ductile failure behavior compared to the other samples.

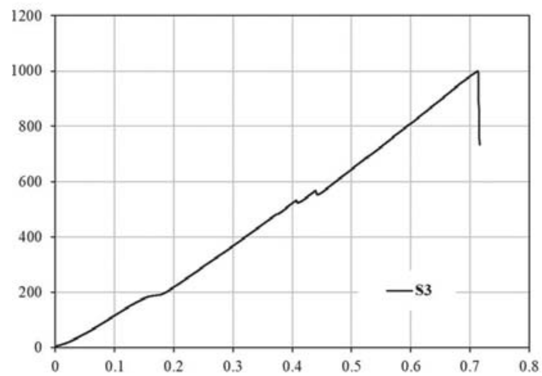

Figure 12. Force–displacement curve of sample S3 (fiberglass group), illustrating the mechanical response under compressive loading

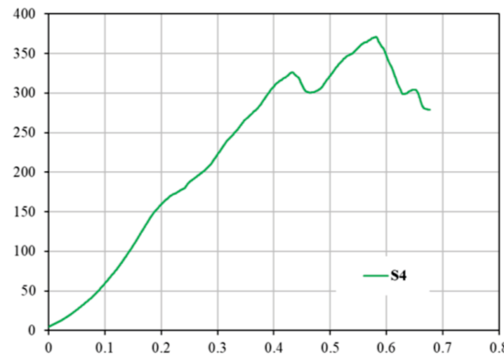

Figure 13. Force–displacement curve of sample S4 (fiberglass group), illustrating the mechanical response under compressive loading

Taking these factors into account, this study aimed to establish a correlation between dental morphology and the biomechanical parameters influencing fracture location and direction. When analyzing force distribution, the upper arch predominantly experiences shear forces, whereas the lower arch is subjected to vertical forces due to the occlusal relationship. This suggests that the fracture pattern may theoretically differ between maxillary and mandibular teeth. The load–displacement curve of sample Z1 (Scheme V) reaches a maximum load of nearly 1350 N, followed by an abrupt drop, indicating brittle fracture characteristic of zirconia.

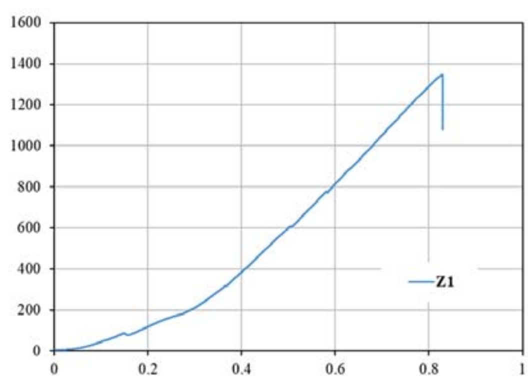

Figure 14. Force–displacement curve of sample Z1 (zirconia group), illustrating the mechanical response under compressive loading

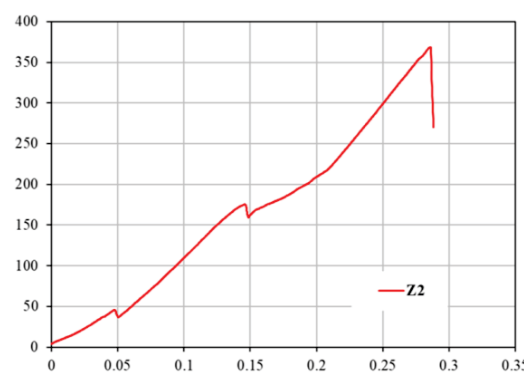

Figure 15. Force–displacement curve of sample Z2 (zirconia group), illustrating the mechanical response under compressive loading

The compression resistance tests for the dental restorations were conducted at the Department of Mechanics and Strength of Materials, Faculty of Mechanics, Politehnica University of Timișoara, under the supervision of Prof. Univ. Negru Radu. The tests were performed using the Zwick/Roell ProLine Z005 universal testing machine, equipped with a 5 kN force cell for uniaxial loading, with an accuracy class of 0.5 in the force measurement range of 1/130%, in accordance with ISO 7500-1. The Zwick/Roell Z005 machine is integrated with the TestXpert III data processing software and is equipped with fixtures for tensile, compression, and three-point bending tests.

The tests were conducted in displacement control mode at ambient temperature, following these steps:

- Preloading at 5 N with a crosshead displacement speed of 1 mm/min;
- Execution of the compression test at a crosshead displacement speed of 1 mm/min;
- Recording of the applied force (F) and the crosshead displacement (Δl) throughout the compression test.

The force was applied using an indenter covered with ceramic material, perpendicular to the occlusal surface of the tooth, until structural failure occurred. Failure was identified by a sudden drop in the measured force. The force-displacement values of the crosshead were recorded in real time using the TestXpert III software.

The results are presented in a table format as follows:

- F_{max} – the maximum force recorded at the moment of failure;
- Δl_{max} – the corresponding crosshead displacement at maximum force.

To ensure a proper comparison of the results, the maximum force (an absolute value) was normalized using the cross-sectional area of the preparation, considered as an ellipse with semi-axes a and b, measured along the mesio-distal and vestibulo-oral directions, respectively:

$$A = \pi ab$$

Thus, the normal compression stress, a specific parameter that eliminates the influence of dental geometry, was calculated as follows:

$$S_{max} = \frac{F_{max}}{A}$$

For samples Z3 and Z4, the first recorded peak force was considered the initiation point of structural failure, with the average values being nearly identical.

In order to evaluate the mechanical behavior of devitalized teeth restored using different techniques, all samples were subjected to compressive strength testing under standardized conditions. This procedure enabled the analysis of the materials capacity to absorb and withstand occlusal forces, as well as their failure thresholds. Fiberglass-based restorations demonstrated a more elastic response to loading, often showing gradual deformation before structural failure. In contrast, zirconia restorations displayed a more rigid behavior, withstanding significantly higher loads but exhibiting sudden fracture patterns. These differences reflect the inherent material properties and suggest distinct clinical indications for each type of restoration.

Table 1 presents the maximum force (F_{max}), cross-sectional area (A), maximum compressive stress (S_{max}), and maximum displacement (Δl_{max}) recorded for each tested sample to better understand the mechanical response of the tested restorations. A compressive load was applied to each sample until structural failure occurred. This analysis provided valuable information on how each material behaves under stress, revealing distinct patterns in strength and deformation. The data includes both groups: S (glass fiber) and Z (zirconia). Average compressive strength values are also provided for each group.

Table 1. Maximum force, cross-sectional area, compressive strength, and displacement at fracture for the tested samples

Type of processing	$F_{max}(N)$	$A\ (mm^2)$	$S_{max}(MPa)$	$\Delta l_{max}(mm)$
S1	1012,70	45,31	22,35	1,675
S2	1951,14	91,85	21,24	1,924
S3	1000,73	71,18	14,06	0,716
S4	370,84	15,67	23,66	0,678
	Average value(MPa)		**20,33**	-
Z1	1344,89	67,82	19,83	0,830
Z2	368,43	37,48	9,83	0,288
Z3	3819,17	87,22	43,79	1,842
Z4	4058,80	82,68	49,09	1,814
	Average value(MPa)		**30,63**	-

Direct or indirect restoration can act as an internal connection, influencing different types of fractures. Radiographic investigations played a crucial role in measuring the sample dimensions and determining the force distribution during the compression tests.

DISCUSSIONS

The results of the compression tests indicated that zirconia-based materials (Z1, Z2, Z3, Z4) exhibited superior compressive strength compared to fiberglass-based materials (S1, S2, S3, S4). The most frequently observed failure modes in devitalized teeth restored with different post-and-core systems (DCRs) are coronal fractures and vertical root fractures [18,19]. Zirconia showed greater resistance to compressive forces, indicating improved durability when subjected to high mechanical loads [20]. Despite having lower resistance than metal-based options, fiberglass materials exhibited sufficient strength for clinical applications, offering increased flexibility that permits minor deformation without breaking [21]. In contrast, zirconia materials were stiffer and showed greater vulnerability to fracturing when subjected to strong lateral forces [22]. These results are consistent with earlier research emphasizing zirconia's high compressive strength alongside its greater brittleness when exposed to tensile stress [23]. Regarding direct restorative techniques, fiberglass-based DCRs were found to adapt more easily to root canals and could be efficiently applied by clinicians. In contrast, zirconia DCRs required a more complex impression-taking process and additional laboratory procedures, which could extend the overall treatment duration [25].

The assessment of adhesion between direct restorative materials and the tooth structure revealed a strong bond, essential for the longevity of restorations [26]. Composite materials employed in direct restorations showed strong adhesion, primarily attributed to improvements in adhesive technologies [27]. This observation is consistent with existing literature, which emphasizes the role of modern bonding agents in ensuring durable restorations [28]. The application of primers and bonding agents significantly improved the integration between the restorative material and the dental substrate, minimizing the risk of debonding and bacterial infiltration [29]. These findings confirm the effectiveness of direct restorative techniques in achieving optimal treatment outcomes, particularly in the corono-radicular reconstruction of devitalized teeth [30].

Aesthetic evaluation of direct restoration techniques highlighted their ability to provide precise adaptation and a reduced treatment time [31]. The increasing variety of restorative materials available on the market allows for a high degree of customization, meeting patients aesthetic expectations [32]. The findings demonstrated that direct restorative materials achieved excellent aesthetic integration with the surrounding dental structures [33].

Functional analysis, including masticatory force simulations, confirmed the materials resistance to wear and mechanical stress [34]. While composite materials provided an excellent aesthetic outcome by closely mimicking the natural tooth color and translucency, slight discoloration was observed over time [35]. These results align with previous research suggesting that although composite materials maintain a stable appearance in the medium term, long-term color stability may be affected by factors such as thermal cycling and exposure to different light sources.

From an economic perspective, the study confirmed that indirect techniques involve higher costs than direct techniques due to the expense of materials, equipment, maintenance, and laboratory procedures [30]. However, these increased costs are justified by the enhanced durability and mechanical properties of indirect restorations, which reduce the need for frequent repairs or replacements [29]. The cost analysis revealed that direct techniques rely on relatively affordable materials such as dental composites and adhesive cements, whereas indirect techniques require more expensive materials, including ceramics and metal alloys, as well as additional expenditures for laboratory fabrication [28]. Additionally, indirect techniques necessitate specialized equipment such as intraoral scanners and CAD/CAM units, increasing the financial investment required for these procedures [27].

Despite the advantages of direct restorations in terms of affordability, ease of application, and aesthetics, certain limitations must be acknowledged [26]. Direct materials, particularly composite resins, are prone to discoloration and wear over time, necessitating periodic maintenance [25]. Furthermore, while their adhesion properties are enhanced by modern bonding systems, the longevity of these restorations may still be influenced by factors such as occlusal forces and patient-specific oral hygiene habits [24]. Future research should focus on optimizing the mechanical properties and color stability of direct restorative materials while exploring new adhesive strategies to further improve the durability of these restorations [23]. Statistical analysis was not performed due to the limited sample size (4 per group), which precluded the application of robust inferential tests. As a result, the findings are presented descriptively, and caution is advised in generalizing the results.

CONCLUSIONS

Fractographic analysis revealed that fracture patterns were strongly influenced by both the type of tooth and the restorative material used. Zirconia-based restorations predominantly exhibited vertical fractures along the long axis of the tooth, suggesting a higher brittleness and susceptibility to stress concentration under compressive forces.

In contrast, fiberglass restorations demonstrated oblique and horizontal fracture patterns, primarily localized at the occlusal surface, indicative of their greater flexibility and ability to distribute mechanical loads more evenly. These findings underscore the critical role of material properties in determining the failure mechanisms of dental restorations, with implications for clinical decision-making and long-term restorative success.

Conflicts of Interest

The authors declare no conflict of interest.

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