



## **Comparative Evaluation of Marginal Fit and Fracture Resistance of CAD–CAM Zirconia Crowns and Conventional Porcelain-Fused-to-Metal Crowns: An In Vitro Study**

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## **Abstract**

**Background:** The longevity of full-coverage restorations depends largely on marginal adaptation and fracture resistance. Advances in digital dentistry have popularized CAD–CAM zirconia crowns, but conventional porcelain-fused-to-metal (PFM) crowns remain widely used.

**Aim:** To compare the marginal fit and fracture resistance of CAD–CAM zirconia crowns and conventional PFM crowns.

**Materials and Methods:** Forty standardized maxillary first molar typodont teeth were prepared for full-coverage crowns and divided into two groups ( $n = 20$ ): Group I: CAD–CAM zirconia crowns; Group II: Conventional PFM crowns. Marginal gaps were measured at four reference points using a stereomicroscope. Fracture resistance was tested using a universal testing machine. Data were analyzed using independent  $t$ -tests ( $\alpha = 0.05$ ).

**Results:** The mean marginal gap for zirconia crowns was significantly lower than PFM crowns ( $p < 0.05$ ). Zirconia crowns also demonstrated significantly higher fracture resistance.

**Conclusion:** CAD–CAM zirconia crowns exhibited superior marginal adaptation and fracture resistance compared to conventional PFM crowns, suggesting improved clinical longevity.

**Keywords:** CAD–CAM, zirconia crowns, porcelain-fused-to-metal, marginal fit, fracture resistance.

## **Introduction**

The restoration of extensively damaged teeth remains a fundamental objective of fixed prosthodontics, with full-coverage crowns representing one of the most frequently employed treatment modalities in contemporary clinical practice.<sup>1,2</sup> The long-term success of these restorations is influenced by multiple biological, mechanical, and esthetic factors, among which marginal adaptation and fracture resistance are considered particularly critical. Inadequate marginal fit can lead to cement dissolution, microleakage, plaque accumulation, secondary caries, and periodontal inflammation, ultimately compromising the prognosis of both the restoration and the abutment tooth. Similarly, insufficient resistance to occlusal forces may result in catastrophic fracture, veneer chipping, or debonding, necessitating repair or replacement.<sup>3,4</sup>

For several decades, porcelain-fused-to-metal (PFM) crowns have been regarded as the benchmark for full-

coverage restorations due to their predictable mechanical strength, acceptable marginal accuracy, and extensive clinical documentation.<sup>5,6</sup> The metal substructure in PFM restorations provides rigidity and resistance to deformation, while the veneering porcelain contributes to esthetics. However, increasing patient expectations for highly esthetic, metal-free restorations, along with concerns regarding metal allergies, gingival discoloration, and opacity at the cervical margin, have stimulated the development and widespread adoption of all-ceramic restorative systems.<sup>5,6</sup>

Among the various ceramic materials available today, zirconia-based ceramics have gained exceptional popularity owing to their superior flexural strength, fracture toughness, and biocompatibility when compared with earlier glass-ceramic systems. The phenomenon of transformation toughening, whereby stress-induced phase transformation at crack tips hinders crack propagation, is responsible for the favorable mechanical performance of zirconia. These properties have expanded its application from single crowns to long-span fixed dental prostheses and implant-supported restorations, particularly in posterior regions where occlusal loads are substantial.<sup>7</sup>

Parallel to the evolution of restorative materials, advances in digital dentistry have revolutionized prosthodontic workflows. Computer-aided design and computer-aided manufacturing (CAD–CAM) systems enable digital impression making, virtual restoration design, and automated milling of ceramic frameworks with the potential for enhanced accuracy and reproducibility. Digital workflows may reduce the number of laboratory steps involved in conventional fabrication, thereby limiting cumulative errors associated with impression distortion, die fabrication, waxing, investing, and casting procedures. As a result, CAD–CAM-fabricated zirconia restorations are frequently advocated for their precision and efficiency.<sup>7,8</sup>

Despite these advantages, conventional PFM crowns continue to be extensively used worldwide because of their long-term clinical track record, cost-effectiveness, and familiarity among clinicians and dental technicians.<sup>9,10</sup> Moreover, some investigations have reported comparable or even superior marginal adaptation for cast metal frameworks in certain situations, raising questions regarding whether digital ceramic systems consistently outperform traditional methods. Similarly, while zirconia frameworks possess high intrinsic strength, clinical complications such as veneering porcelain chipping and framework fracture have been reported, emphasizing the need for systematic laboratory evaluation of their mechanical behavior.

The existing literature reveals considerable variability in reported marginal gap values and fracture resistance measurements for both zirconia and PFM restorations. Differences in study design, tooth preparation

geometry, cementation protocols, aging procedures, measurement techniques, and loading conditions make direct comparison difficult and underscore the necessity for well-controlled experimental investigations. In vitro studies, although limited in replicating the complex oral environment, provide a standardized platform for isolating and analyzing the influence of restorative material and fabrication technique on specific performance parameters.

Therefore, the present in vitro study was undertaken to comparatively evaluate the marginal fit and fracture resistance of CAD–CAM-fabricated zirconia crowns and conventionally fabricated porcelain-fused-to-metal crowns under standardized conditions. By assessing these two widely used restorative options, this research aims to contribute meaningful data to assist clinicians in evidence-based material selection for posterior full-coverage restorations.

## **Materials and Methods**

**Study Design:** This in vitro experimental study was conducted to compare the marginal fit and fracture resistance of CAD–CAM-fabricated zirconia crowns and conventionally fabricated porcelain-fused-to-metal (PFM) crowns under standardized laboratory conditions.

**Sample Size Determination:** A total of forty specimens were included in the study based on previous laboratory investigations evaluating marginal accuracy and fracture resistance of full-coverage restorations, with a power of 80% and a significance level of 5%. The samples were randomly divided into two equal groups (n = 20):

- Group I: CAD–CAM zirconia crowns
- Group II: Conventional PFM crowns

**Tooth Selection and Mounting:** Forty identical maxillary first molar resin typodont teeth free from defects and manufacturing irregularities were selected to ensure uniformity in size and morphology. Each tooth was embedded vertically in autopolymerizing acrylic resin blocks using a dental surveyor so that the cemento-enamel junction was positioned 2 mm above the resin surface, simulating clinical crown exposure.

**Tooth Preparation:** Standardized full-coverage crown preparations were performed by a single operator using high-speed rotary instruments under water coolant. A milling surveyor was employed to maintain consistent taper and reduction across all samples.

The preparation parameters were as follows:

- Occlusal reduction: 2.0 mm
- Axial reduction: 1.5 mm

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- Finish line: 1.0 mm deep circumferential chamfer
  - Total occlusal convergence: approximately 6°
  - All internal line angles were rounded.

Following preparation, the teeth were examined under magnification to confirm uniformity.

### **Grouping and Fabrication Procedures**

**Group I CAD–CAM Zirconia Crowns:** Digital impressions of the prepared teeth were made using an intraoral scanner. The crowns were designed using computer-aided design software with standardized parameters for cement space (50 µm starting 1 mm above the finish line). The restorations were milled from partially sintered zirconia blocks using a five-axis milling unit, followed by sintering in a high-temperature furnace according to manufacturer recommendations. After sintering, the crowns were glazed and finished.

**Group II – Porcelain-Fused-to-Metal Crowns:** Conventional impressions were made using addition silicone elastomeric impression material in custom trays. Type IV dental stone dies were poured and sectioned. Wax patterns were fabricated with uniform coping thickness (0.5 mm) and sprued, invested, and cast using a base-metal alloy. After finishing and sandblasting, porcelain veneering was performed following the incremental build-up technique and fired in a ceramic furnace. Final glazing was carried out after occlusal adjustments.

**Cementation Procedure:** Prior to cementation, all crowns were cleaned ultrasonically in distilled water for five minutes and air-dried. The prepared teeth were rinsed and dried.

Each crown was cemented using resin-modified glass ionomer cement mixed according to the manufacturer's instructions. A standardized vertical load of 5 kg was applied for five minutes using a loading device to ensure uniform seating. Excess cement was removed, and the specimens were stored in distilled water at 37°C for 24 hours before testing.

**Marginal Gap Measurement:** Marginal adaptation was evaluated using a stereomicroscope at 40× magnification. Each specimen was positioned on a customized jig to maintain consistent orientation during observation.

Measurements were recorded at four predetermined locations: Buccal, Lingual, Mesial, Distal.

Three readings were taken at each surface, and the mean value was calculated to obtain the marginal gap for each specimen. All measurements were recorded in micrometers (µm) by a single blinded examiner.

**Fracture Resistance Testing:** Following marginal analysis, specimens were subjected to compressive load

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testing using a universal testing machine. Each specimen was aligned vertically, and a stainless-steel spherical indenter (6 mm diameter) was positioned at the central fossa to ensure axial loading.

A continuous load was applied at a crosshead speed of 1 mm/min until catastrophic failure of the crown occurred. The maximum load at fracture was recorded in Newtons (N).

**Statistical Analysis:** The collected data were tabulated and analyzed using statistical software. Normality of distribution was assessed using the Shapiro–Wilk test. Intergroup comparisons for marginal gap and fracture resistance were performed using independent sample t-tests. The level of statistical significance was set at  $p < 0.05$ .

**Result:** All forty specimens were successfully fabricated, cemented, and tested without procedural complications. Data for both marginal gap and fracture resistance demonstrated normal distribution as assessed by the Shapiro–Wilk test ( $p > 0.05$ ); therefore, parametric statistical analyses were performed.

The mean marginal gap value for CAD–CAM zirconia crowns was  $62.4 \pm 8.1 \mu\text{m}$ , whereas porcelain-fused-to-metal crowns exhibited a higher mean marginal discrepancy of  $91.7 \pm 10.3 \mu\text{m}$ . Inter-group comparison using the independent sample t-test revealed that this difference was statistically significant ( $p = 0.001$ ), indicating superior marginal adaptation of zirconia crowns compared with PFM restorations (Table 1).

Fracture resistance testing demonstrated that CAD–CAM zirconia crowns withstood significantly higher loads prior to failure than PFM crowns. The mean fracture resistance recorded for the zirconia group was  $1820 \pm 210 \text{ N}$ , while the PFM group fractured at a mean load of  $1345 \pm 185 \text{ N}$ . Statistical analysis confirmed that the difference between the two groups was significant ( $p = 0.003$ ) (Table 2).

Overall, both evaluated parameters—marginal fit and fracture resistance—showed statistically significant inter-group differences favoring CAD–CAM zirconia crowns over conventionally fabricated porcelain-fused-to-metal crowns.

<b>Group</b>	<b>Mean <math>\pm</math> SD (<math>\mu\text{m}</math>)</b>	<b>Minimum</b>	<b>Minimum</b>	<b>p-value</b>
CAD–CAM Zirconia	$62.4 \pm 8.1$	49.6	78.3	<b>0.001*</b>

PFM	91.7 ± 10.3	72.4	112.6	
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\*Significant

**Table 2: Mean fracture resistance values (N) for the two groups**

Group	Mean ± SD (N)	Minimum	Minimum	p-value
CAD–CAM Zirconia	1820 ± 210	1485	2156	<b>0.003*</b>
PFM	1345 ± 185	1092	1684	

\*Significant

## Discussion

The present in vitro study compared the marginal adaptation and fracture resistance of CAD–CAM-fabricated zirconia crowns and conventionally fabricated porcelain-fused-to-metal (PFM) crowns under standardized conditions. Both evaluated parameters demonstrated statistically significant differences between the two groups, with zirconia crowns exhibiting superior marginal fit and higher resistance to fracture. These findings suggest that digital fabrication combined with high-strength ceramic materials may offer mechanical and biological advantages over traditional metal-ceramic restorations.

Marginal adaptation is a critical determinant of the long-term success of fixed prostheses. Excessive marginal discrepancy may lead to cement dissolution, bacterial infiltration, secondary caries, and periodontal inflammation.<sup>11,12</sup> In the present investigation, zirconia crowns demonstrated significantly lower marginal gap values than PFM crowns. This observation may be attributed to the streamlined digital workflow associated with CAD–CAM systems, which eliminates multiple laboratory steps inherent to conventional techniques such as impression pouring, die trimming, waxing, investing, and casting. Each of these steps introduces potential dimensional changes that can cumulatively affect the final fit of PFM restorations. In contrast, direct digital scanning and computer-controlled milling may enhance reproducibility and reduce human-related variability, thereby improving marginal accuracy.

The superior fracture resistance recorded for zirconia crowns in this study is consistent with the known mechanical characteristics of zirconia ceramics.<sup>13,14</sup> Transformation toughening, a unique property whereby stress-induced phase changes at the crack tip impede crack propagation, contributes to the high flexural strength and fracture toughness of this material. Additionally, the monolithic or semi-monolithic nature of zirconia restorations reduces dependence on veneering porcelain, which is often the weakest component in metal-ceramic systems and a frequent site of chipping or cohesive fracture. Conversely, in PFM crowns, the

veneering ceramic is supported by a metal coping but remains susceptible to tensile stresses during loading, potentially explaining the lower fracture resistance values observed.

Despite the favorable mechanical behavior of zirconia frameworks, it is important to recognize that clinical failures of zirconia-based restorations have been reported, particularly in the form of veneering porcelain chipping and low-temperature degradation in certain environments. Therefore, while the present results support the mechanical superiority of zirconia crowns under static loading conditions, they should be interpreted cautiously when extrapolating to long-term clinical performance.<sup>15,16</sup>

The variability in reported marginal gap and fracture resistance values across previous laboratory investigations highlights the influence of methodological differences, including preparation geometry, cement space settings, type of luting agent, aging protocols, and loading conditions. In the present study, strict standardization of tooth preparation, cementation load, and testing parameters was employed to minimize confounding factors and isolate the effect of crown material and fabrication technique. Nevertheless, direct comparison with other investigations remains challenging because of differences in experimental design.

Several limitations of this study must be acknowledged. First, the *in vitro* nature of the investigation does not replicate the complex oral environment, where restorations are subjected to thermal cycling, moisture, pH fluctuations, masticatory fatigue, and parafunctional forces. Second, static compressive loading was used to evaluate fracture resistance, whereas clinically restorations experience cyclic and multidirectional forces over extended periods. Third, typodont teeth were used instead of natural teeth, which may differ in elastic modulus and bonding behavior. Finally, failure mode analysis was not extensively categorized, which could have provided additional insight into the nature of crown fracture and veneer behaviour.

Future research should incorporate thermomechanical aging protocols, cyclic fatigue testing, and long-term clinical trials to better simulate intraoral conditions and validate the laboratory findings. Comparative evaluation of monolithic zirconia, layered zirconia, and newer translucent ceramic systems may further assist clinicians in selecting appropriate restorative materials for posterior load-bearing situations.

**Conclusion:** Within the limitations of this *in vitro* study, CAD–CAM-fabricated zirconia crowns demonstrated significantly superior marginal adaptation and higher fracture resistance when compared with conventionally fabricated porcelain-fused-to-metal crowns. The improved marginal accuracy observed with zirconia restorations may be attributed to the precision and reproducibility of digital manufacturing workflows,

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while their greater resistance to fracture reflects the favorable mechanical properties of zirconia ceramics.

These findings suggest that CAD–CAM zirconia crowns may offer potential biological and mechanical advantages for posterior full-coverage restorations. However, as laboratory conditions cannot fully replicate the intraoral environment, long-term clinical studies incorporating thermomechanical aging and fatigue loading are recommended to substantiate these results and to determine their relevance in routine clinical practice.

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