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# Comparative Analysis of Fracture resistance and Fracture mode of Implant-Supported Zirconia Crowns Using Different Implant Abutment Designs: An In Vitro Study

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## Abstract

**Background:** The effectiveness of implant-supported restorations largely relies on their capacity to resist functional forces. To enhance the mechanical performance of zirconia restorations, different abutment designs have been developed and are currently in use. **Aim:** This study aimed to evaluate the fracture resistance and fracture modes of implant-supported zirconia crowns fabricated with different abutment configurations after artificial aging. **Materials and Methods:** 36 implant analogs were arbitrarily assigned to three groups (n = 12). Group A: one-piece hybrid abutment crowns (HAC). Group B: Two-piece restorations hybrid abutment with a separate crown. Group C: stock titanium abutments with crown. Artificial aging was applied to all specimens (500 thermo-cycle and 120,000 mechanical cyclic). The fracture resistance was assessed by a universal testing machine, the fracture modes were evaluated under (SEM) at ×30, ×300, and ×5000 magnifications. **Results:** Group A showed the highest fracture resistance mean (2243.2 ± 234.2N), Group B recorded the lowest value (1819.6 ±173.2 N). The difference among the groups was statistically significant ($P < 0.05$). SEM analysis revealed different fracture morphologies in the three different groups. **Conclusion:** The one-piece restoration revealed highest fracture resistance. However, the fracture resistance values in the different designs were higher than the average masticatory forces in the premolar teeth, supporting their potential for clinical use.

**key words:** Implant-supported zirconia crowns, Hybrid abutment crowns, Titanium base, Fracture resistance, Failure mode.

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## Introduction

Dental implants are considered a reliable option for missing teeth substitute, supported by consistent evidence showing high survival rates and good long-term outcomes) Papaspyridakos et al., 2012; Srinivasan et al., 2012). Studies have informed that single crowns placed on a dental implant maintain longevity rates about ninety percent over five -years, highlighting their effectiveness in restoring both function and appearance (Wittneben et al., 2014).

Titanium abutments have long been regarded as the reference standard because of their mechanical durability and predictable performance. Despite these advantages, esthetic shortcomings are frequently reported, particularly in cases with a thin gingival biotype (Bonyatpour et al., 2023). In response to increasing esthetic demands, ceramic alternatives—most notably zirconia abutments—have been introduced (Guilherme et al., 2016; Gehrke et al., 2015). However, zirconia presents certain drawbacks, including limited mechanical fit and greater risk of brittleness (Baldassarri et al., 2012; Elsayed et al., 2018).

Hybrid abutments were developed to overcome the drawbacks of conventional designs by using Ceramic structure bonded to a titanium base. This approach combines mechanical resistance with long–term durability of titanium with the esthetic advantages of ceramics. Incorporating a Ti-base has been shown to enhance biomechanical performance, enabling the abutment to withstand higher occlusal forces while improving the fracture resistance of the ceramic component. Furthermore, the titanium-to-titanium connection along the implant–abutment junction provides greater stability, protects the implant surface, and avoids the dimensional limitations of prefabricated abutments. Collectively, these features reduce the risk of complications such as soft-tissue irritation, metallic visibility, and cervical fractures commonly reported with zirconia abutments (Al-Thobity, 2022; Graf et al., 2023).

Implant-supported restorations utilizing titanium bases are commonly produced using two main techniques, in the first method, both the crown and abutment are manufactured as a unified monolithic component, which is then cemented over the Ti-base and the restoration is fixed to the implant using a screw-retained mechanism, this configuration merges the advantages associated with screw-retained and cement-retained designs, enabling retrievability, reducing the likelihood of subgingival cement residues, and supporting peri-implant tissue health alongside improved esthetics. The second method adopts a two-piece design, where the crown and abutment are manufactured separately, here, the abutment is cemented over the Ti-base and secured to the implant, while the crown is subsequently cemented over it (Nouh et al., 2019; Yıldız et al., 2024).

Fracture resistance is a main mechanical factor influencing the extended period success of implant-supported restorations (Çötert et al., 2025). While earlier studies have compared one-piece and two-piece prosthetic designs, the two-piece restorations in those investigations were fabricated without a screw-access channel (Donmez et al., 2021; Roberts et al., 2018). Consequently, additional studies are needed to assess two-piece designs that

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incorporate screw access, as this feature may alter both biomechanical behavior and clinical performance.

Accordingly, the present investigation conducted to examine two-piece prosthetic designs that incorporate a screw-access channel. The present research aimed to assess the fracture resistance and fracture modes of zirconia restorations fabricated with different abutment configurations following artificial aging.

## Materials and Methodologies

**Ethical approval:** Institutional ethical approval was obtained from the Mustansiriyah University Institutional Review Board (Reference: MUO PR 34, December 11, 2024).

Thirty-six implant analogs (ANY RIDGE, MEGAGEN, Korea) were mounted in 3D-printed PMMA blocks, scanned with a desktop scanner (Medit T710, Korea) (Sabih and Jasim, 2024).

Samples were arbitrarily categorized into three groups (n=12) according to restoration design:

Group A consisted of a one-piece hybrid abutment–crown assembly supported by a Ti-base.

Group B included a two-component restoration composed of a hybrid zirconia abutment and a separate zirconia crown.

Group C utilized a prefabricated titanium abutment combined with a zirconia crown, as illustrated in Figure 1.

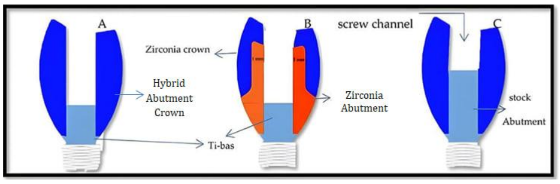


**Figure1:** Cross-sectional schematic diagram showing the restorative designs used in the three experimental groups.

Crown parameters: Maxillary right first premolar, with standardized dimensions the length is 11.5 mm، the width is 8.5 mm. A uniform cement gap of 40 µm. Each crown included a screw access channel extending from the center of the occluding surface. To ensure consistency and minimize variability, a single STL file was used for all designs with identical cement spacing (Pacheco et al., 2021).

Fabrication: The Ti-base was chosen from the software library of CAD-CAM, based on the specifications of the implant system used (MEGA GEN – ANY RIDGE, Korea), measuring (4.0 mm D) and (4.5 mm in L). For Group A, the hybrid abutment crown was virtually designed directly over the Ti-base as in Figure 2. In Group B, a custom zirconia abutment (length 7 mm) was modeled on the selected Ti-base, followed by the crown construction over it. For Group C, a prefabricated abutment with a diameter of 4 mm and a length of 7 mm (MEGA GEN – ANY RIDGE) was chosen from the system library. The crown was then designed to fit over this abutment. All digital models were standardized to ensure uniform morphology and structural features across groups.

The completed designs were saved in STL format and then transferred to CAM (Computer-Aided Manufacturing) software to prepare them for the milling process. Milling was performed with aid of a five-axis milling system (ARUM 5X-500) used for (CAD/CAM operation, Australia). Zirconia restorations were sintered at 1550 °C. (Rajab and Jasim, 2024).

After fabrication, all specimens underwent polishing and glazing, as surface irregularities can act as crack initiation sites and reduce resistance to fracture.

DOI: 10.32828/mdj.v22i1.1251

Earlier studies have suggested that glazing can seal minor surface imperfections and assist in partial crack repair (Lu et al., 2023).

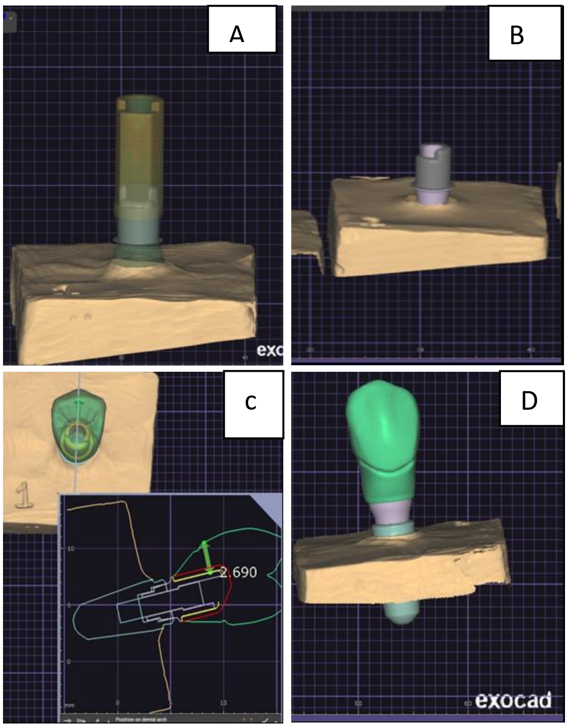


**Figure 2:** Digital workflow. (A) Scan body, (B) Ti-base selection, (C) Crown design, (D) Final abutment-crown configuration

**Surface Treatment:**

The Ti-bases, stock titanium and custom zirconia abutments, and the internal (intaglio) surfaces of the crowns underwent airborne-particle abrasion using 50 µm $Al_2O_3$ particles, subsequently, a universal adhesive primer was applied. Cementation was performed using RelyX U200 self-adhesive resin cement. The selection of this cement aimed to minimize technique sensitivity while providing uniform stress distribution (Tyor et al., 2023).

**Cementation Protocol:**

The cementation procedures varied among the groups. For Group A, hybrid abutment –assemblies were bonded to the Ti-base in one step with a self-adhesive resin cement. For Group B, the cementation procedure was performed in two steps: Initially, the customized zirconia abutment was bonded over the Ti-base, and subsequently, the zirconia crown was bonded to the abutment, as illustrated in Figure 3. For Group C, a single-step cementation of the crown to the stock titanium abutment was performed. In all groups, screw- channels were sealed with Teflon tape prior to cement application to prevent cement entrapment. Cement was placed onto the intaglio surface, and restorations were seated under gentle finger pressure. Residual cement was carefully eliminated with aid of fine brush, Light polymerization was performed for 20 seconds on each crown surface to enhance polymerization. This approach aligns with reports indicating that dual-cured resin cements achieve superior mechanical properties when supplemented with adequate light exposure (Sabih and Jasim, 2024). Finally, a custom loading device was used to apply a vertical force of 50 N for 6 minutes to ensure complete seating of the restorations (Jamal and Jasim, 2023).

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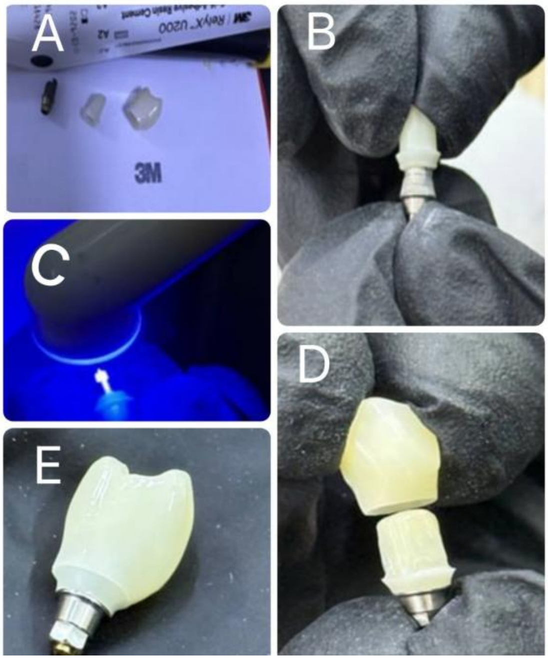


Figure 3: Two-step cementation procedure for the two-piece restoration of Group B: (A) component of Group B, (B) luting the custom-made zirconia abutment to the Ti-base, (C) Light curing, (D) cementing the crown onto the zirconia abutment, (E) the final restoration after completion of cementation.

**Artificial Aging**

Artificial aging was performed by two procedures: thermocycling and dynamic mechanical loading. Samples underwent temperature cycling from 5 °C to 55 °C, with each bath having a 30-second holding period, using an automated thermocycling apparatus that alternated specimen immersion in hot and cold-water baths (Sabih and Jasim, 2024; Salah and Sleibi, 2024). Mechanical aging was simulated by applying 120,000 loading cycles at a force of 50 N with a frequency of 1Hz, corresponding to approximately six months of simulated oral function. A custom load-cycling device equipped with 4 mm styluses was used, operating in water-filled chambers under computer control, as illustrated in Figure 4. The presence of water during loading further enhanced clinical relevance by reproducing wet fatigue conditions (Abd-Almohaimen et al., 2023; Ashour et al., 2024).

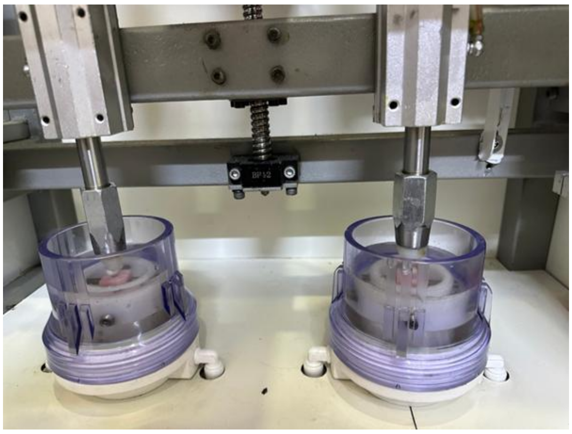

**Figure 4:** cyclic loading machine

**Fracture Resistance Test**

For mechanical testing, a double-blind approach was adopted by coding all specimens (Figure 5). A custom-fabricated steel specimen holder was used to secure each sample, the specimens were fixed in position by tightening a screw, ensuring that the longitudinal axis of the virtual maxillary first premolar crown was oriented perpendicularly to the occlusal plane. The standardized occlusal morphology allowed reproducible positioning of all specimens within the testing machine.

To minimize stress concentration, a 1 m-thick sheet of rubber was placed between the loading rod and the crown. Each crown was loaded at the central fossa using a 5 mm diameter metal tip to ensure precise axial load application, this perpendicular compressive force was selected to simulate the functional forces most commonly exerted on maxillary premolars in vivo (Bonyatpour et al., 2023). The fracture test carried out with aid of a Universal Testing Machine (LARYEE, Technology

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University). The crosshead of the testing machine advanced at 0.5 mm per minute. (Figure 6). Loading was applied to each specimen until structural failure occurred, and the highest load at failure was automatically documented in Newtons (N) via the computer software connected to the testing unit (Donmez et al., 2021).

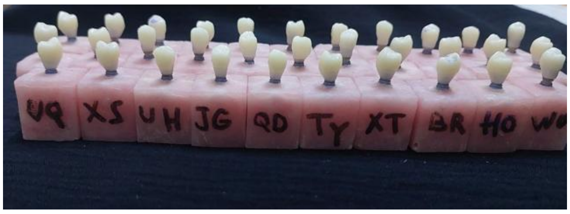

**Figure 5:** Coding of the samples by double blind technique.

Fracture modes were assessed under SEM (The Thermo Scientific Axia ChemiSEM ,1–30 kV, ~3 nm resolution at 30 kV, real-time EDS mapping) at magnification, ×30, ×500, and ×5000 to classify cohesive or adhesive failures (Bonyatpour et al., 2023; Pashley et al., 2011).

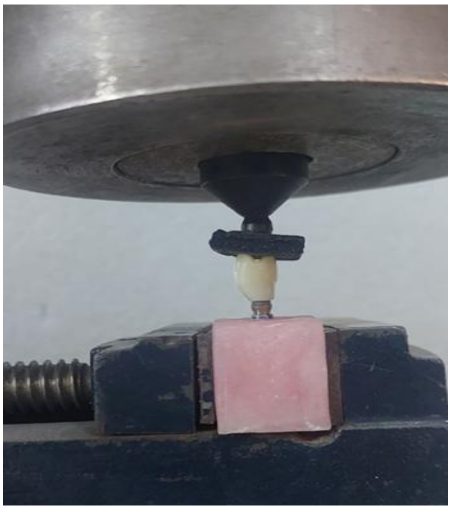

**Figure 6:** The samples in the testing machine with the rubber.

**Results**

The Shapiro–Wilk test confirmed normal distribution of fracture resistance values for all groups. Table 1

**Table 1:** Normality Test (Shapiro–Wilk)

A one-way ANOVA showed significant differences among the groups ($p < 0.0001$), with Group A exhibiting the highest mean fracture resistance (2243.2± 234.2 N), followed by Group C (1965.9± 169.1N), while Group B recorded the lowest (1819.6 ± 173.2 N). Table 2.

| Groups | Statistic | Df | Sig.* |
|---|---|---|---|
| A | 0.9 | 12 | 0.54 |
| B | 0.9 | 12 | 0.73 |
| C | 0.9 | 12 | 0.84 |

**Table 2:** One-way ANOVA

| Groups | N | Mean | Sd | Min. | Max. | F | P value* |
|---|---|---|---|---|---|---|---|
| A | 12 | 2243.2 | 234.2 | 1757.0 | 2596.0 | 13.46 | <0.001 |
| B | 12 | 1819.6 | 173.2 | 1608.0 | 2077.0 | | |
| C | 12 | 1965.9 | 169.1 | 1695.0 | 2210.0 | | |

DOI: 10.32828/mdj.v22i1.1251

Post-hoc Tukey's test showed that Group A demonstrated significantly higher strength compared to Groups B and C ($p < 0.05$). However, there were no statistically significant differences between Groups B and C($p>0.05$).

**Table 3.** post-hoc (Tukey's test) comparisons

| Group (I) | Group (J) | Mean Diff | SE | p-value | Lower CI | Upper CI |
|---|---|---|---|---|---|---|
| A | B | 423.6 | 146. | <0.001 | -628.1 | -219.2 |
| A | C | 277.4 | 146. | 0.006 | -481.8 | -72.9 |
| B | C | -146.3 | 146.0 | 0.199 | -58.2 | 350.7 |

**Fracture Mode Analysis**

Scanning electron microscopy (SEM) revealed that fracture initiation region was located on the occlusal compression side, immediately beneath the hemispherical indenter, as illustrated in Figure 7 (A, B, C). The three groups exhibited distinct morphological features. In Group A (Fig 8), the fracture surfaces showed rough areas, deep grooves, and sharp-edged topography. Fragmented structures and remnants of the luting material were also identified along the fracture interface. These characteristics indicated a predominantly cohesive failure within the restorative complex, though with a more irregular and complicated morphology compared to the other groups.

In Group B (Fig 9), the fractured surfaces appeared smoother and more uniform. Partial adherence of material suggested cohesive failure within the cement layer or the abutment, but with a more compact and consistent fracture pattern.

In Group C (Fig 10), the surfaces were comparatively flat with straighter fracture lines and minimal bonding remnants. This cleaner interface indicated mainly adhesive failure at the crown–abutment junction.

DOI: 10.32828/mdj.v22i1.1251

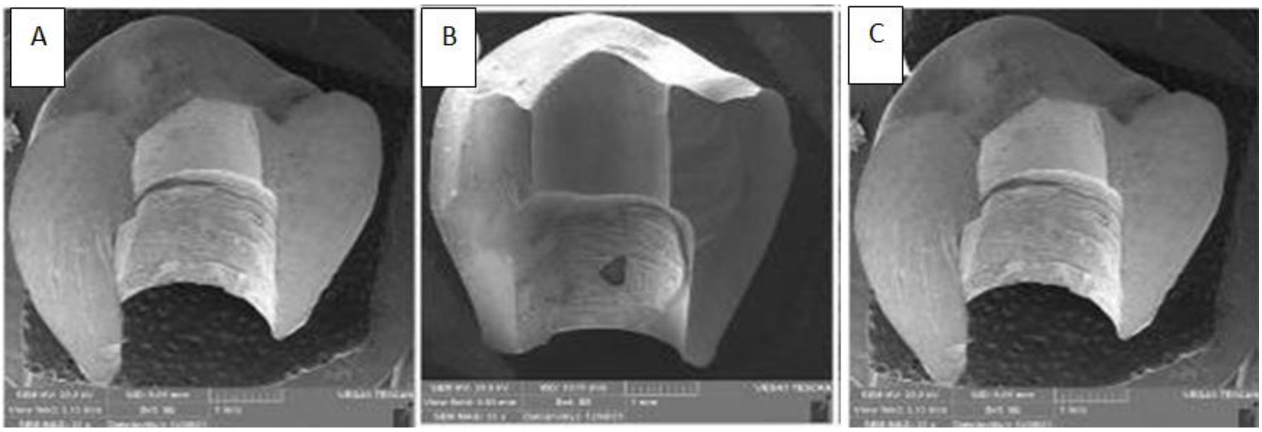


**Figure 7.** SEM micrographs showing the fracture origin at a magnification of ×30 with a scale bar of 5000 µm: (A) Group A, (B) Group B, and (C) Group C.

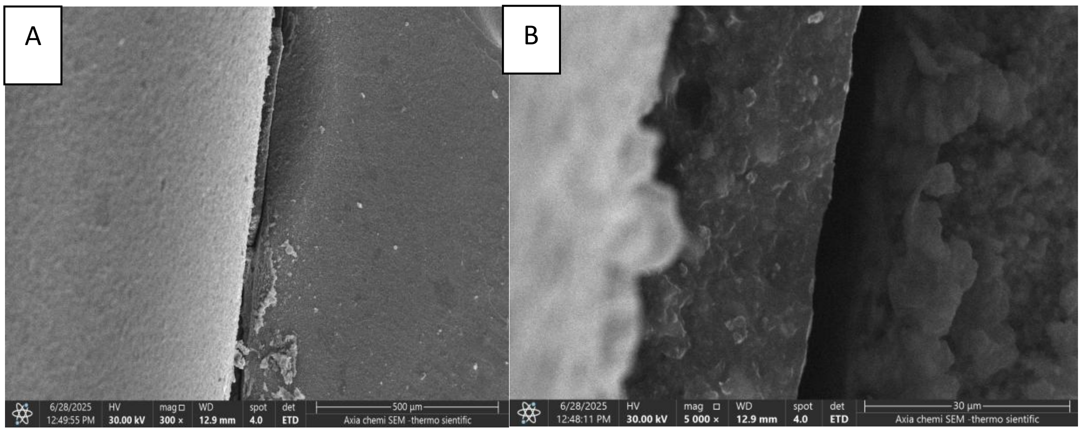


**Figure 8**. SEM micrographs illustrating the fracture mode of Group A at a voltage of 30 kV: (A) magnification ×300 with a scale bar of 500 µm, and (B) magnification ×5000 with a corresponding scale bar.

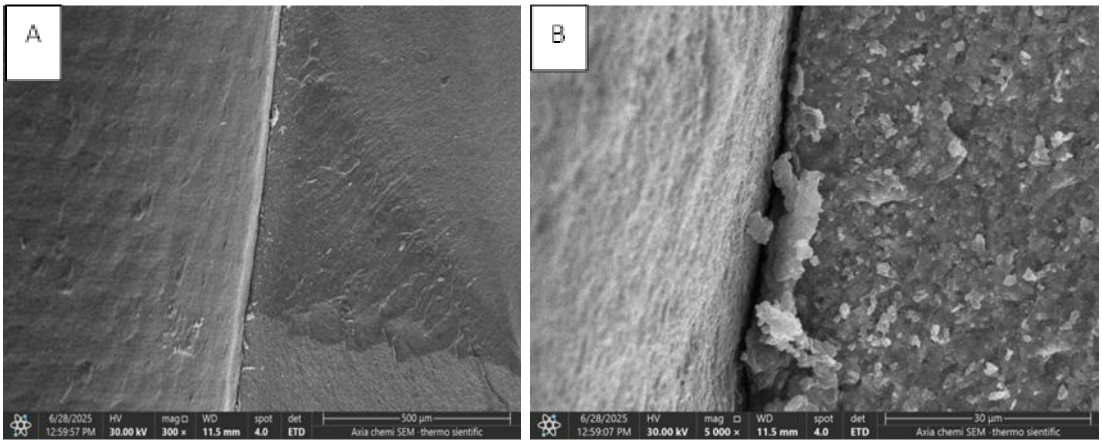


**Figure 9.** SEM micrographs illustrating the fracture mode of Group B at a voltage of 30 kV: (A) magnification ×300 with a scale bar of 500 µm, and (B) magnification ×5000 with a scale bar of 30 µm.

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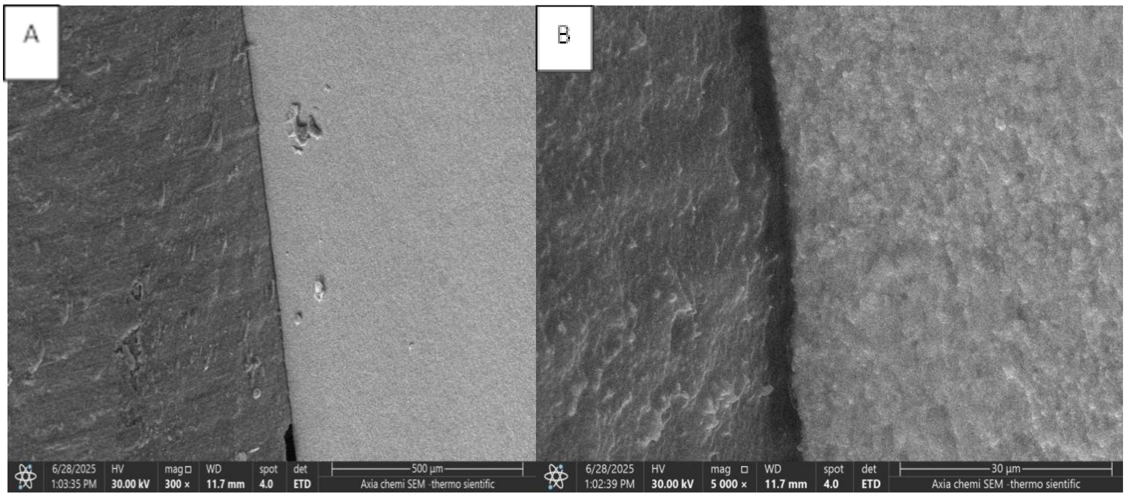


**Figure 10.** SEM micrographs illustrating the fracture mode of Group C at a voltage of 30 kV: (A) magnification ×300 with a scale bar of 500 µm, and (B) magnification ×5000 with a scale bar of 30 µm.

## Discussion

### Effect of abutment design

The abutment design significantly affected fracture resistance of implant-supported crowns. The null hypothesis was therefore rejected based on the statistical analysis ($P < 0.001$). Group A (one-piece zirconia restorations on Ti-base) showed the highest mean fracture resistance (2243.27±234.21N). The enhanced performance observed in this group may be explained by the direct integration of the zirconia hybrid abutment crown with the Ti-base, which reduces the number of interfaces and potential weak points, thereby enhancing overall structural stability (Roberts et al., 2018).

Group C (prefabricated titanium abutment with a zirconia crown) recorded an intermediate mean fracture resistance (1965.91 ± 169.14 N). The presence of a titanium abutment likely provided a more ductile and resilient foundation compared to the all-ceramic configuration in Group B, enabling improved stress absorption and resistance to catastrophic failure (Çötert et al., 2025).

Group B (two-piece zirconia restoration consisting of a Ti-base, a custom zirconia abutment, and a zirconia crown) exhibited the lowest mean fracture resistance (1819.64± 173.23 N). This may be due to the presence of multiple adhesive interfaces along with the natural brittleness of zirconia, factors that collectively increase the risk of failure.

### Effect of screw channel

The presence of a screw channel in all restoration designs acts as a stress concentration site, which may reduce fracture resistance. Ahmed et al. similarly confirmed that screw access channels compromise the mechanical strength of restorations, concluding that intact occlusal surfaces exhibit the highest resistance (Ahmadi et al., 2023). This factor has not been considered in previous studies, including those evaluating two-piece designs.

### Comparison with previous studies

The findings of this study concur with those of Çötert et al., who demonstrated that hybrid-abutment crowns show significantly greater fracture resistance than screwmentable restorations supported by stock abutments. This superiority was attributed to the more integrated design of hybrid-abutment crowns, which promotes better load distribution and minimizes stress concentration at the crown–abutment junction (Çötert et al., 2025).

Similarly, Roberts et al. reported that fabricating the restoration as a single unit, without the inclusion of an intermediate cement layer, improves the overall strength of the prosthesis, by contrast, when the crown and abutment are produced separately, an additional interface is introduced, which compromises the mechanical integrity relative to a full-contour abutment–crown configuration (Roberts et al., 2018).

The findings of this study are in contrast with Domneiz et al., who reported lower resistance values for one-piece restoration compared to the restoration consist of two-piece. This difference may be explained by design variations: Their two-piece crowns lacked screw channels, whereas the current investigation incorporated them, creating stress concentration sites that reduce fracture resistance (Domneiz et al., 2021). In addition, Domneiz et al. tested multiple restorative materials, while the present work focused solely on zirconia and included both thermal and mechanical aging, offering a more controlled and clinically relevant evaluation.

The data from this research are partially in concurred with those of Nouh et al., who reported no significant difference in fracture resistance between hybrid abutment crowns and hybrid abutments restored with isolated crowns. Notably, some zirconia one-piece restorations in their study withstood loads exceeding 3,500 N without fracturing, redirecting stress to the implant–abutment connection. In contrast, all restorations in the current investigation incorporated screw access channels, including the two-piece group, which may have reduced fracture strength. (Nouh et al., 2019).

These findings are in line with those of Naumann et al., who concluded that there are no statistically significant differences between screw-retained one-piece restorations and cemented two-piece lithium disilicate restorations on bone-level implants, as determined by both objective assessment and subjective evaluations (Naumann et al., 2025).

**Clinical Implications**

The findings of this study have practical relevance for clinical practice. The one-piece hybrid abutment crowns demonstrated higher fracture resistance, suggesting a lower risk of restoration failure under occlusal loading. two-piece designs were associated with slightly lower strength, indicating that careful planning of the abutment design is important. Importantly, all restorations exceeded the maximum masticatory forces of premolar teeth (200–445 N), confirming that they are clinically acceptable for premolar replacement (Donmez et al., 2021; Ferrairo et al., 2021).

**Fracture Mode Analysis**

SEM observations showed that fractures typically originated on the occlusal compression side beneath the indenter, a finding consistent with previous reports

DOI: 10.32828/mdj.v22i1.1251

describing Hertzian cone crack initiation under localized loading (Ellakwa et al., 2011; Alghazawy et al., 20232; Bonyatpour et al., 2023).

In Group A, the irregular topography with luting remnants indicated a complex cohesive similar to the cohesive fracture patterns reported by Bonyatpour et al. in one-piece zirconia–Ti-base restorations. (Bonyatpour et al., 2023).Group B presented smoother fracture surfaces, suggesting cohesive failure within the cement layer or zirconia abutment. This may reflect stronger bonding performance, supported by literature showing that material compatibility and modern adhesive systems enhance stress distribution and bond durability (Pashley et al., 2011; Gökçe et al., 2025).In contrast, Group C showed cleaner fracture lines with minimal cement residues, consistent with adhesive failure at the crown–abutment junction. Such failures have been widely reported in zirconia-based restorations, especially when conventional cements are used without zirconia-specific primers. (Pjetursson et al., 2015).

The limitations of the present study were that the applied cyclic loading protocol of approximately 120,000 cycles provided a standardized simulation of early functional loading; however, it may not fully represent long-term intraoral fatigue, which typically involves millions of cycles over several years. Additionally, the in vitro design cannot replicate the full complexity of the oral environment, including dynamic loading angles, moisture, temperature fluctuations, and biological factors such as saliva and bone support.

## Conclusions

Based on the limitations associated with this in vitro study, Hybrid abutment crowns demonstrated superior mechanical performance compared to two-piece restorations and stock titanium abutments. Nevertheless, all tested configurations exceeded physiological occlusal forces, supporting their clinical reliability for premolar implant rehabilitation.

## Conflict of interest

The authors reported that they have no conflicts of interest.

## Acknowledgments

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