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In-vitro mechanical performance of three CAD-CAM bar designs for implant-supported metal–resin hybrid prostheses: a preliminary pilot study

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ABSTRACT

Background: Implant-supported hybrid metal–resin prostheses are widely used to rehabilitate edentulous patients. However, fractures of the veneering resin and screw complications remain common mechanical failures. Advances in CAD-CAM design and laser sintering technology may improve the structural integrity of these restorations.
Aims: To conduct a preliminary in-vitro evaluation of the fracture resistance of veneering resin in three CAD-CAM–designed bar configurations fabricated by laser sintering, describing their mechanical behavior and failure patterns under compressive stress.
Methods: Three bar designs (inverted T, L-shaped, and Ackerman circular) were digitally created and manufactured in cobalt–chromium using laser sintering. Each bar was veneered with autopolymerizing acrylic resin and subjected to compressive loading up to 1000 N at a 30° angle, in accordance with ISO 14801. Simultaneously, acoustic emission analysis was performed to detect microcracks and structural failures.
Results: No fractures of the veneering resin were observed. Mechanical failures occurred as deformation or fracture of prosthetic screws, beginning at 600 N. Acoustic emission detected early microcracks between 160 N and 400 N, and main fracture peaks between 627 N and 871 N. Among the three samples, the inverted T-shaped bar sustained the highest load before failure in this pilot test.
Conclusion: In this pilot in-vitro study, the veneering resin showed high resistance under simulated masticatory loading. The combination of CAD-CAM design, laser-sintered fabrication, and retentive elements may enhance mechanical performance. Further studies with larger sample sizes and cyclic loading are warranted to validate these preliminary findings.

1. Introduction

The management of edentulous patients has increasingly become a challenge for clinicians. Reports of functional difficulties, reduced masticatory efficiency, and lack of support with conventional complete dentures have led to the use of fixed implant-supported prostheses, which provide improved retention and stability, offering advantages in comfort and long-term predictability.[1]

A hybrid prosthesis consists of a cast, milled, or laser-sintered metal framework with an I- or U-shaped cross-sectional design, incorporating retentive features that allow the pink resin veneering material and prefabricated resin teeth to adhere mechanically, forming a single structure that is screwed to implants to function as a fixed prosthesis. This type of restoration has been successfully used in edentulous patients since 1985 and remains in use today, with follow-up studies reporting success rates of 95 % at 10 and 15 years.[2] A key factor for long-term clinical success lies in the design and fabrication of the metal frameworks that support implant prostheses. Multiple approaches to framework design have been reported. In I-bar designs, the apical vestibular and lingual portions of the structure serve as support for the teeth, while

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in L-bar designs, the teeth are supported apically by the horizontal component of the L-beam. These frameworks aim to provide adequate support for artificial teeth and the base to minimize fracture risk, with at least 3 mm of vertical height recommended to ensure sufficient rigidity. Original designs were developed empirically, without the benefit of laboratory testing.[3]

The prosthetic framework is generally fabricated from a metal structure covered with acrylic resin and screwed to osseointegrated implants, forming a removable prosthesis that can only be detached by a clinician. A minimum resin thickness of 1.5 mm is recommended to reduce the risk of fracture, and metallic frameworks should ideally have a modulus of elasticity above 80,000 MPa to resist deformation and cantilever-related fractures.[4,5] Although much clinical research has focused on implant survival and biological complications in partial edentulism, prosthodontic and biomechanical failures in full-arch fixed prostheses have received less attention.[6,7] Reported mechanical complications include screw loosening, fracture of veneering resin or prosthetic teeth, and screw or framework failure. These failures are often caused by biomechanical stress, which increases proportionally with occlusal forces, making it a major risk factor in implant-supported restorations.[8–10]

Fabricating hybrid prosthesis frameworks by laser sintering reduces porosity, thereby decreasing susceptibility to corrosion, and shows lower misfit levels compared to conventional casting techniques.[8]

Recently, Real-Osuna et al. conducted a retrospective study of patients rehabilitated with metal–resin hybrid prostheses over one year at the Implantology Department of Bellvitge Dental Hospital. They concluded that the most common complication was mucositis, followed by resin fracture. Several factors contribute to the high rate of resin fractures, including the lack of mechanical retention for the teeth within the metal framework design, permanent elastic deformation due to variable cantilever lengths, and the type of opposing dentition.[9]

Therefore, it is advisable to incorporate retentive elements into the design of metal frameworks—regardless of alloy or manufacturing technique—to reduce fracture rates and improve long-term clinical outcomes.

Despite the widespread use of hybrid metal–resin prostheses, mechanical failures such as resin chipping, screw deformation, and veneering material detachment remain frequent. However, there is limited experimental evidence comparing how different bar designs affect the mechanical support of veneering resin under functional loading. The inverted T, L-shaped, and Ackerman circular designs are commonly used in clinical practice, yet their comparative mechanical behavior has not been quantified. Therefore, conducting a preliminary in-vitro assessment of commonly used bar designs may offer valuable insight into their mechanical behavior and failure tendencies. This pilot approach may help guide future studies with larger samples and more comprehensive modeling of clinical conditions.

2. Objective

2.1. Primary objective

To conduct a descriptive in-vitro pilot evaluation of the mechanical behavior of three CAD-CAM bar designs used in metal–resin hybrid prostheses, focusing on their performance under compressive loading and the failure patterns identified through acoustic emission analysis.

2.2. Specific objectives

1. To determine the load levels at which initial microfracture signals and structural failures occur for each bar configuration.
2. To qualitatively compare the acoustic emission patterns and failure modes across the three designs.
3. To explore which bar design withstands the highest compressive force before mechanical failure in this pilot setting.

3. Materials and methods

This study was designed as an exploratory in-vitro pilot evaluation aimed at characterizing the mechanical behavior of three CAD-CAM bar configurations used in metal–resin hybrid implant-supported prostheses.

3.1. Bar design and fabrication

Three bar types were designed using a CAD-CAM system (Exocad software) (Fig. 1), enabling precise duplication of each metal structure. One specimen per design was fabricated to validate the testing protocol, identify preliminary failure patterns, and assess whether the bar geometry or the veneering material constituted the structural weak point.

- **Inverted T-shaped bar**: included retention holes; 4 mm height, 5 mm base width, 2 mm lower step height (Fig. 2).
- **L-shaped bar**: featured long vertical retentive spikes; 5 mm width, 3 mm height, 0.5 mm lower portion (Fig. 3).
- **Ackerman circular bar**: had vertical spikes of various sizes; 4 mm diameter and height (Fig. 4).

These configurations were selected due to their clinical relevance and distinct biomechanical characteristics. All bars were fabricated in cobalt–chromium alloy by selective laser melting, ensuring precision, passive fit, and avoidance of misfit issues common with traditional casting.

3.2. Prosthetic setup and mounting

Each bar was mounted on two multi-unit analogs in mandibular positions 32 and 42. The prosthetic simulation included the six lower incisors, matching mesiodistal and cervico-incisal dimensions. The teeth (Acry Plus Ruthinium) were veneered with Palapress Vario acrylic resin, applied over a 1.5 mm uniform layer. Final contours were shaped manually by wax-up and finished with carbide and tungsten burs, followed by polishing with pumice and KMG liquid (Candulor) (Fig. 5).

3.3. Load application and mechanical testing

To simulate occlusal loading, a Co–Cr test base was designed in Meshmixer with a 30° inclination (30 mm diameter, 20 mm height), onto which bars were secured using screws and analogs from GMI Dental Implantology, S.L. (Lleida, Spain).

Mechanical testing was performed at the University of Barcelona

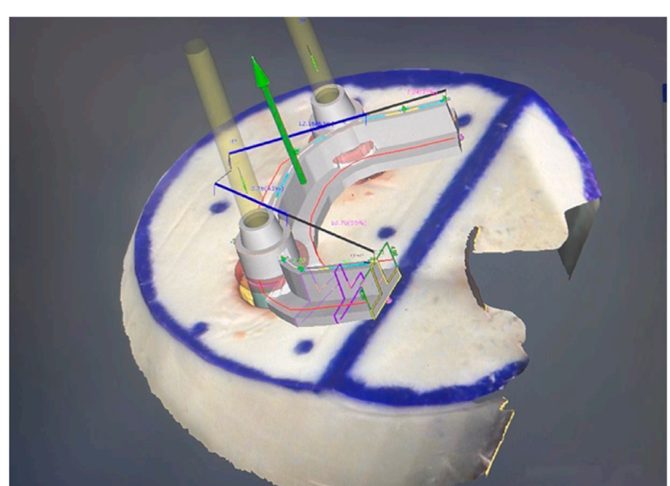

Fig. 1. Exocad bar design.

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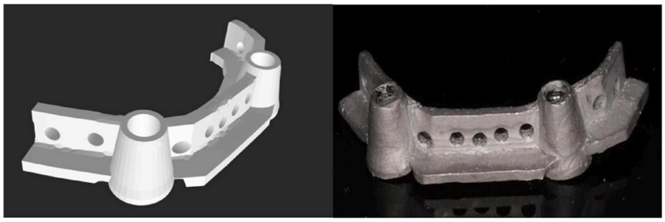

Fig. 2. Inverted T-shaped bar with additional retention holes, with dimensions of 4 mm in height, a base width of 5 mm, and a lower step height of 2 mm.

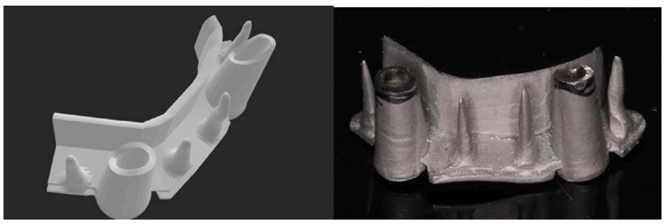

Fig. 3. L-shaped bar with long vertical spikes as retentive elements, with section parameters of 5 mm in width, 3 mm in height, and 0.5 mm in the lower portion.

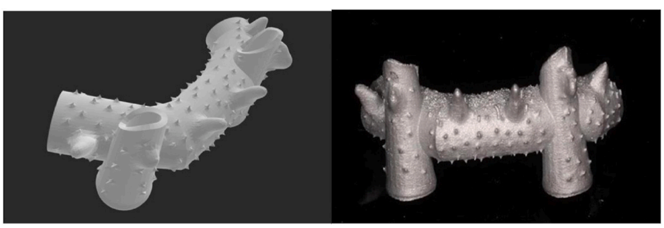

Fig. 4. Ackerman circular bar with vertical spikes of different sizes, 4 mm in diameter and 4 mm in height.

Fig. 5. The teeth were mounted on each bar.

using a universal testing machine (Zwick/Roell Z-005, Zwick/Roell S.L.) (Fig. 6). Load calibration was verified per manufacturer guidelines. Each sample was loaded vertically on the anterior teeth surface at a constant speed of 0.01 mm/min. Compressive force ranged from 200 to 1000 N, based on literature-reported masticatory forces (300–600 N) (Fig. 7). The test followed ISO 14801 guidance for implant-supported systems.

3.4. Acoustic emission monitoring

During mechanical loading, acoustic emission (AE) was recorded using compression plates with 9.5 mm integrated piezoelectric transducers, positioned 2 mm from the sample. Ultrasonic coupling was ensured via a thin petroleum jelly layer. Voltage signals were pre-amplified (60 dB) and recorded via a PCI2 system (Euro Physical Acoustics, Individual AE). AE events were defined at a 23 dB threshold and concluded when voltage remained below threshold for >200 μs. Event energy was computed as the time integral of squared voltage, normalized by a 10 kΩ reference resistor. Signals from the most active channel were used to avoid double counting and ensure optimal contact.

Fig. 6. Universal testing machine (Zwick/Roell Z-005, Zwick/Roell S.L).

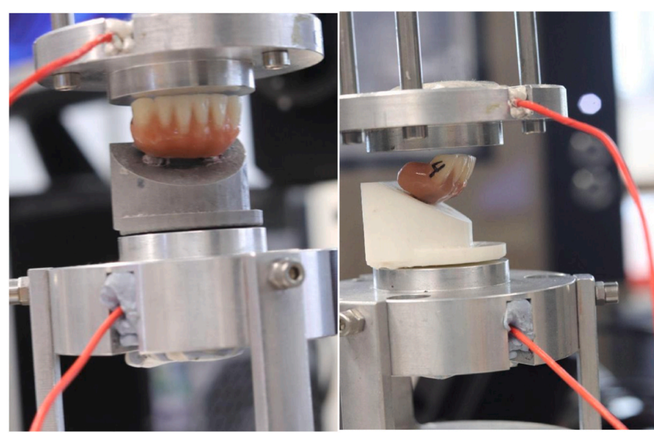

Fig. 7. The applied force ranged from 200 to a maximum of 1000 N, considering that the masticatory force reported in the literature varies between 300 and 600 N. The load was applied directly on the teeth of each bar.

4. Results

A descriptive study was conducted, collecting data on resistance and retention efficacy as a function of the material. Since the exact fracture strength of the veneering material was unknown, one test was carried out for each bar design. As each bar configuration was tested once in this pilot study, results are reported descriptively without statistical inference.

Initially, six tests were planned (two per bar type), but when the prototypes were subjected to loading, no fracture of the veneering material was observed; instead, deformation of the multi-unit prosthetic screws occurred. For this reason, testing was limited to the 3 bar designs under a maximum load of 1000 N, applied progressively from 0 N to 1000 N. For the acoustic emission test, the sensors were connected to a data acquisition system (Physical Acoustics Corporation, PCI-2 Based AE System). See expanded Table 2 for complete acoustic and mechanical outcomes.

4.1. Summary of findings

During mechanical testing, screw deformation was observed for all 3 bar designs, while no visible fractures were detected in the veneering resin or the artificial teeth. For the Ackerman/round bar, screw deformation occurred at **627.58 N**. In the L-shaped bar, deformation was recorded at **750.19 N**, and in the inverted T-shaped bar, deformation occurred at **871.39 N**.

The acoustic emission analysis showed differences among the 3 bar designs. In the Ackerman/round bar, the initial microcrack was detected at 200 N, and a major acoustic emission peak was recorded at 627 N, corresponding to structural fracture. For the L-shaped bar, the first microcrack appeared at 400 N, with the fracture peak observed at 750 N. In contrast, the inverted T-shaped bar exhibited the earliest microcrack, at 160 N, while the main peak occurred at 871 N, indicating fracture of the structure (Fig. 8).

In the acoustic emission analysis, the small initial peaks correspond to early microcrack events occurring within the metal–resin interface or the screw–bar assembly. These events reflect localized stress concentrations but do not imply structural failure. In contrast, the large final peak recorded for each bar design represents the moment of macroscopic structural failure, typically associated with screw deformation or fracture. This distinction clarifies the relationship between the acoustic signal pattern and the mechanical behavior observed during loading.

5. Discussion

This pilot study combined compressive mechanical testing with acoustic emission analysis, offering complementary insights into early microcrack formation and final structural failure. The use of CAD-CAM design and laser-sintered cobalt–chromium fabrication enabled high reproducibility and precise control of bar geometry, minimizing variability between specimens. Evaluating three clinically common bar configurations under standardized loading conditions also provided relevant preliminary information on how framework design may affect the mechanical behavior of implant-supported hybrid prostheses.

Mechanical complications are among the most frequent issues in metal–resin hybrid prostheses, compromising both function and esthetics, and emphasizing the need for continued research to identify and mitigate failure sources. Screw-related complications are particularly prevalent, regardless of prosthetic design, as the screw–implant connection is vulnerable to loosening or fracture due to force direction, magnitude, and the mechanical limitations of the components.[11] Araujo and Miluska (2022) reported screw loosening in 17.78 % of cases.[12] Several contributing factors have been identified, including insufficient preload, overtightening-induced deformation, parafunctional forces, occlusal interferences, and excessive cantilevers.[13]

In our study, deformation and fracture began at 600 N. A maximum

Table 1
Bar designs and dimensions.

Type of bar	Height	Width	Retention elements
Inverted T bar (Canada type)	4 mm	5 mm	Perforations
L-shaped bar (Hybrid design 2)	3 mm	5 mm	Vertical spike-type retentions
Round bar (Ackerman type)	4 mm	4 mm	Vertical spike-type retentions

Table 1.Bar Designs and dimensions used.

Table 2
Mechanical test results with acoustic emission and failure types.

Bar Design	Fmax (N)	dL at Fmax (mm)	AE Onset (N)	Failure Type
Ackerman/Round bar	627.59	3.16	400	Screw fracture
L-shaped/Hybrid design	750.20	3.67	300	Screw fracture
Inverted T-shaped bar	871.40	3.22	160	Screw deformation

Table 2. Mechanical test results for each bar design, including maximum compressive force (Fmax), deformation at Fmax (dL), acoustic emission onset (AE Onset), and observed failure type. The data reflect single-specimen pilot tests performed under ISO 14801 conditions.

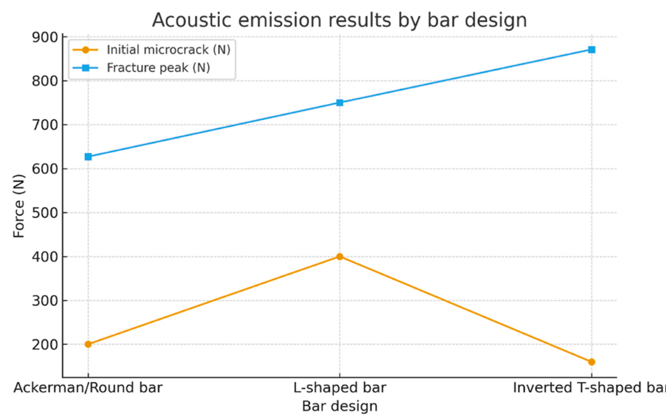

Fig. 8. Acoustic emission results for the 3 bar designs. The graph shows the force at which the initial microcrack was detected (circles) and the force corresponding to the fracture peak (squares).

load of 1000 N was selected based on prior literature indicating that certain materials can withstand deformation beyond 1200 N.[14] The physiological bite force in the molar region of healthy adults typically ranges from 300 to 600 N, with higher values often observed in bruxism cases.[15]

One of the most common complications in hybrid prostheses is the fracture of veneering material, with nearly 70 % of implant-supported hybrid prostheses exhibiting some degree of fracture over time. Successful performance of acrylic resin prostheses requires sufficient material thickness and support from the underlying bar. Optimal results are more likely when frameworks are designed in accordance with pre-planned tooth positions, ideally leaving 1.5–2 mm of space for prosthetic materials such as acrylic resin, composite, or reinforced polymers.[16] These parameters were followed in our test models.

Fractures may be attributed to material strength limitations, design errors, or laboratory inaccuracies. Although many of these factors are manageable with technical precision, the high rate of resin fractures suggests ongoing challenges.[17] In our study, incorporating retentive elements in the bar appeared to improve fracture resistance, as no resin fractures occurred within the test range. These elements—e.g., nail-heads, retention loops, or undercuts—were distributed along the bars to avoid interference with tooth positioning or chimney emergence.[3] Mechanical bonding between the resin and metal was enhanced by well-defined finishing lines. Additionally, CAD-CAM and laser-sintered fabrication improved adaptation, minimizing stress transmission and promoting passive fit, a key factor for long-term success.[18]

High impact resistance and flexural strength are desirable for denture base acrylics. PalaXtreme is among the first self-curing resins to surpass ISO 20795 thresholds for tensile strength (2.39 MPa m^1/2) and fracture work (1.128 J/m^2). According to literature, cobalt–chromium bars exhibit an elastic modulus of 224,000 MPa, compared to 4100 MPa for PMMA [19–21]. Cr-Co bars show a fracture limit of 710 MPa. These materials follow a fatigue curve depending on the number and intensity of masticatory cycles. One large force can induce immediate failure, while repeated subcritical forces may also lead to fracture over time.[22]

Carmona et al.[23] conducted a finite element analysis of three hybrid bar designs, simulating mandibular arches with anterior and posterior teeth up to the first molar. A 400 N load was applied, using axial forces on posterior teeth and 45° oblique buccolingual forces on anterior teeth. Each tooth received 28.5 N. Stress concentration was highest in the anterior region. Titanium bars showed greater stress (22.16 MPa) than Cr-Co (14.69 MPa)—a 33.7 % difference—though both remained below fracture thresholds (titanium 880 MPa, Cr-Co 710 MPa).[24] The maximum load applied in this study (1000 N) falls within the fracture range reported in Carmona's study (600–1000 N).

Fatigue fractures occur when cyclic loads generate microscopic cracks that grow over time until structural failure.[24] Acoustic emission is an effective method to monitor crack propagation in real-time by detecting nano-to micrometer-level displacements caused by internal stress changes. This technique has been used to evaluate failure mechanisms in loaded materials.[25] In our study, acoustic emission responses across all 3 bar designs were comparable to forces observed in physiological mastication, supporting its potential role in predicting mechanical complications.

Although fractures of veneering resin were anticipated, only screw deformation or fracture was observed. These findings suggest that retentive element integration, sufficient veneering thickness, and the combination of CAD-CAM design with laser-sintered fabrication may reduce fracture risk in hybrid prostheses.

As a pilot study, statistical analysis was not performed due to single-sample testing per design—a common limitation in feasibility protocols aimed at validating experimental setups and identifying failure patterns.

Several limitations must be acknowledged. Only one sample per bar design was tested, preventing inferential statistical analysis. Cyclic loading and fatigue performance were not evaluated. Furthermore, in-vitro conditions do not fully simulate intraoral factors like humidity, temperature variations, or long-term wear. Observed failures occurred mainly at the screw level, which may not fully represent veneering resin behavior in clinical settings. The absence of cyclic testing, the single-specimen design, and lack of a control group limit the generalizability of these findings.

Future studies should include controlled cyclic loading over extended durations, as clinical behavior under functional forces remains incompletely understood. Finite element simulations may help evaluate design-specific behaviors and refine bar geometry. Further research could explore simplified bar designs to clarify whether structural shape plays a role in fracture resistance.

Despite the limitations, these preliminary findings suggest that optimizing bar geometry and using effective retentive elements may enhance the mechanical reliability of implant-supported metal–resin hybrid prostheses and reduce the risk of common technical complications.

6. Conclusions

In this preliminary in-vitro pilot study, none of the bar designs exhibited visible fractures of the veneering resin under loading up to 1000 N. Instead, deformation or fracture occurred at the level of the prosthetic screws, suggesting that the screw–bar assembly was the weakest structural component under the tested conditions.

Among the three configurations, the inverted T-shaped bar demonstrated the highest resistance prior to structural failure. However, due to the exploratory nature of this study and the use of single specimens without cyclic or fatigue loading, these findings cannot be extrapolated to clinical scenarios.

Within these limitations, the results indicate that bar geometry and the inclusion of retentive elements may influence the transmission of forces to both the veneering material and the screws. Further research with larger sample sizes and long-term cyclic loading is needed to determine whether these initial trends translate into clinically significant differences. Additionally, no statistical analysis was performed due to the single-sample design; therefore, the findings should not be interpreted as definitive evidence of superiority among the tested bar configurations.

Patient's/Guardian's consent

Not applicable.

Ethical clearance

It is not applicable to this study as it is in vitro.

Sources of funding

No funds have been required.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Sergi torne duran reports article publishing charges was provided by University of Barcelona. Sergi torne duran reports a relationship with University of Barcelona that includes: board membership and employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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