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Design Matters

How Occlusal Surface Geometry Influences the Fracture Resistance of CAD/CAM Restorations

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Abstract

This study evaluated the effect of occlusal surface design (anatomic vs. non-anatomic) on the fracture resistance of monolithic zirconia full crowns fabricated using CAD/CAM technology. A mandibular first molar was prepared with 1.5 mm occlusal and 1.0 mm axial reduction (90° shoulder finish line) to serve as a master die. The die was duplicated using a heavy-body silicone index to produce 40 type IV stone dies, randomly divided into two groups) n=20 :(Group A (full anatomic occlusal design) and Group B (modified non-anatomic/flat occlusal design). Crowns were milled via CAD/CAM, sintered, and seated on their respective dies. Axial loading was applied using a rounded indenter in a Universal Testing Machine at a crosshead speed of 1 mm/min) until fracture, and the maximum load (N) was recorded. Group A exhibited a mean fracture resistance of 2063 N (range 1903-2173 N). Group B demonstrated a highly comparable mean fracture resistance of 2059 N (range 1987-2125 N). Statistical analysis showed no significant difference between the two groups ($p = 0.905$). Modifying the occlusal design from anatomic to flat does not significantly affect the fracture resistance of monolithic zirconia crowns. Both designs demonstrated exceptional load-bearing capacities that comfortably exceeded maximum clinical masticatory forces.

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Introduction

Computer-aided design and computer-aided manufacturing (CAD/CAM) technology have transformed modern dentistry by enabling the fabrication of highly accurate and esthetic restorations through digital workflows. Despite its advantages, the initial cost of scanners, design software, and milling units remains relatively high and may pose financial challenges for some dental practices. Additionally, successful implementation requires specialized training, and the technique is sensitive to errors during scanning or digital design, which may negatively affect the final restoration. Nevertheless, continuous technological advancements are steadily reducing costs and improving user-friendliness, making CAD/CAM systems more accessible worldwide [1,2].

Clinically, CAD/CAM technology has become integrated into nearly all dental specialties. It is widely applied in the fabrication of crowns, veneers, inlays, onlays, and fixed partial dentures, as well as implant abutments, surgical guides, orthodontic appliances such as clear aligners, and complete dentures. The versatility, precision, and reproducibility of CAD/CAM restorations make this technology an essential component of prosthodontics, restorative dentistry, orthodontics, and implantology [3].

Looking toward the future, CAD/CAM dentistry is expected to further evolve through advancements in artificial intelligence, faster milling systems, improved 3D-printing technologies, and the development of novel biocompatible materials. These innovations are anticipated to enhance accuracy, efficiency, and aesthetic outcomes. As digital workflows become increasingly automated and widely adopted, CAD/CAM technology will play a central role in delivering high-quality dental care [4].

A dental CAD/CAM system consists of three main components, each of which plays a critical role in the accuracy, mechanical performance, and fracture resistance of the final restoration.

Data Acquisition (Scanning): Digital impressions are obtained using either intraoral or extraoral scanners. Intraoral scanners capture the three-dimensional morphology of prepared teeth, adjacent structures, and occlusion directly from the patient's mouth. The accuracy of the scan directly affects marginal fit, occlusal anatomy, and stress distribution within the restoration. Errors at this stage may result in improper occlusal contacts and increased risk of fracture [2].

Computer-Aided Design (CAD): The CAD phase involves virtual design of the restoration using specialized software. This stage allows precise control over occlusal surface design, cusp inclination, fissure depth, and thickness of restorative material. The ability to digitally modify occlusal anatomy is particularly relevant to studies comparing different occlusal surface designs and their influence on fracture resistance [3].

Computer-Aided Manufacturing (CAM): The CAM stage involves fabrication of the restoration through subtractive milling or additive manufacturing. Milling is most used for zirconia and other ceramics, where restorations are milled from pre-sintered or fully sintered blocks. Manufacturing accuracy and tool precision significantly affect internal fit and mechanical strength [5].

There are many advantages of CAD/CAM technology, including high precision and reproducibility of restorations, improved marginal and internal fit, accurate reproduction of occlusal anatomy, reduced human error compared with conventional techniques, enhanced material homogeneity and structural integrity, and digital storage and reproducibility of restoration designs [3].

And there are many limitations and disadvantages of CAD/CAM technology, such as high initial cost of scanners, software, and milling units, requirement for specialized training and technical expertise, technique sensitivity during scanning and design stages, potential for occlusal inaccuracies due to scanning errors, milling limitations for complex occlusal morphologies, equipment maintenance, and software upgrade costs. However, continuous technological advancements are improving system reliability, reducing costs, and expanding accessibility [4].

Zirconia is a polycrystalline ceramic material that has become one of the most important restorative materials in modern dentistry. Unlike glass ceramics, zirconia does not contain a glassy phase, which contributes to its superior mechanical properties, including high flexural strength and fracture toughness. These characteristics make zirconia particularly suitable for high-load bearing restorations fabricated using CAD/CAM systems [6].

Pure zirconia exists in three crystallographic phases depending on temperature: monoclinic (room temperature), tetragonal (above 1170°C), and cubic (above 2370°C). To stabilize zirconia at room temperature and improve mechanical performance, stabilizing oxides such as yttrium oxide are added. This stabilization is critical for maintaining structural integrity and fracture resistance under clinical conditions [7].

The introduction of CAD/CAM technology played a pivotal role in the widespread adoption of zirconia. CAD/CAM milling enabled precise fabrication of zirconia restorations with consistent material properties and improved fit. Over time, advancements in material science led to the development of high-translucency zirconia, expanding its indications from posterior frameworks to monolithic anterior restorations [3,8].

Zirconia exhibits exceptional mechanical behavior due to a phenomenon known as transformation toughening. When subjected to stress, tetragonal zirconia grains transform into the monoclinic phase, resulting in volumetric expansion that induces compressive stresses around crack tips. This mechanism effectively arrests crack propagation and significantly enhances fracture resistance [9].

Early zirconia materials were characterized by high opacity due to light scattering at grain boundaries and alumina content. This limited their use in aesthetically demanding regions. Advances in powder processing, grain size control, and yttria concentration have led to the development of high-translucency zirconia materials that better mimic natural tooth structure [6].

However, increased translucency is achieved at the expense of reduced transformation toughening, which may compromise fracture resistance. This trade-off between esthetics and strength is particularly relevant when evaluating different occlusal surface designs, as sharper cusps and deeper fissures may increase stress concentration in more translucent zirconia materials [10].

Zirconia's mechanical behavior, combined with CAD/CAM fabrication, makes it an ideal material for fracture resistance research. The interaction between occlusal surface design, material thickness, sintering parameters, and loading conditions directly influences failure patterns. Therefore, zirconia restorations provide a reliable model for comparative evaluation of different occlusal surface designs in CAD/CAM systems [6,8].

Anatomical occlusal designs feature well-defined cusps and grooves that closely resemble natural dentition, providing improved masticatory efficiency through effective shearing and grinding of food. The cuspal inclines allow stable intercuspation and balanced occlusion; however, these designs require precise arrangement, as minor errors can lead to occlusal interferences and denture instability [11,12].

In contrast, non-anatomic or zero-degree occlusal designs lack cuspal anatomy and present flat occlusal surfaces, particularly in patients with resorbed ridges or compromised neuromuscular control. Although non-anatomic designs offer easier adjustment and improved tissue tolerance, they exhibit reduced masticatory efficiency compared with anatomical designs.

The selection of occlusal design depends on multiple factors, including ridge anatomy, functional demands, esthetic expectations, and clinician preference. Anatomical designs are preferred in patients with favorable conditions, while non-anatomic designs are advantageous in compromised cases where stability and tissue preservation are prioritized [13].

Tooth preparation is a fundamental step in fixed prosthodontics, aiming to provide adequate space for restorative materials while preserving tooth vitality, periodontal health, and structural integrity. Improper preparation can compromise crown retention, fracture resistance, and pulpal health [14].

Key principles include preservation of tooth structure, appropriate retention and resistance form, structural durability, marginal integrity, and periodontal considerations. Ideal taper ranges between 6° and 10°, with sufficient crown height and auxiliary features used when necessary to enhance retention. Adequate occlusal and axial reduction ensures material thickness, prevents fracture, and maintains occlusal anatomy [15].

Finish line design varies according to restorative material, with chamfer margins commonly used for metal crowns, deep chamfers or shoulders for all-ceramic restorations, and shoulder-with-bevel designs for porcelain-fused-to-metal crowns. Proper finishing, smoothing, and water cooling are essential to prevent pulpal damage and ensure optimal restoration fit [16].

Fracture resistance is defined as the maximum force a tooth or restorative material can withstand before failure and is typically measured in Newtons during in-vitro testing. It is a critical determinant of restoration longevity and clinical success [17].

Several factors influence fracture resistance, including remaining tooth structure, cavity design, restoration type, cementation method, and occlusal forces. Conservative preparations, rounded internal line angles, cuspal coverage, and adhesive resin cements significantly enhance fracture resistance. Posterior teeth and patients with parafunctional habits are exposed to higher occlusal stresses, increasing fracture risk [15,18].

Clinically, materials and designs with higher fracture resistance are preferred in high-load

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areas. The interaction between occlusal surface design and CAD/CAM restorative materials is therefore crucial in optimizing fracture resistance and long-term clinical outcomes [14,16].
Aim of this study: To evaluate the effects of occlusal surface design on the Fracture resistance of a full Zirconia crown. Designing and milling in the modern technique of the CAD CAM system.

Materials and Methodos

Sample Preparation and Grouping
A total of 40 standardized die samples were prepared for this study. A lower first molar ("mandibular first molar") was selected and prepared with a 90° shoulder finish line. The tooth reduction parameters were strictly controlled.
Occlusal reduction: 1.5mm at the center.
Axial reduction: 1.0mm

Figure 1. Cast with preparation tooth with 90° shoulder angles.

The prepared tooth was sectioned using a saw to create the master die. To achieve a sample size of n = 40, the master die was duplicated using a heavy-body silicone index impression material (Alphasil Perfect Putty Soft / Zhermack Indurent Gel) to pour 40 identical stone die samples.
The samples were randomly and equally divided into two experimental groups (20 specimens per group) based on the design anatomy:

Group A (Full Anatomy): Zirconia crowns designed with a full anatomical occlusal surface over the 90° shoulder prepared die.
Group B (Non-Anatomy / flat): Zirconia crowns designed with a non-anatomical configuration over the 90 ° shoulder prepared die.
The fabrication process followed a fully digitized CAD/CAM workflow:
Digital Scanning: Each stone die was positioned on a desktop scanner device to capture all surface details, generating a high-resolution 3D digital file.
Computer-Aided Design (CAD): The 3D files were imported into Exocad software to design the restorations for both Group A (full anatomy) and Group B (flat).

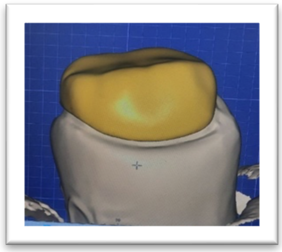

Figure 2. Exocad design.

Computer-Aided Manufacturing (CAM) & Milling: The finalized CAD designs were exported as 3D files into CAM software (MillBox). The restorations were nested within pre-sintered zirconia blanks (Aconia ST White Zirconia Block, Besmile) and milled using a 5-axis milling machine (MAXX DS200-5Zc).
Finishing and Coloration: After milling, the crowns were carefully separated from the zirconia blank using a diamond bur to cut the excess sprues. The specimens then underwent coloration by applying a specialized coloration liquid.
Sintering and Crystallization Following the coloration process, the green-state zirconia crowns were placed into a high-temperature zirconia sintering furnace (NHT High Technology). The crystallization process was executed according to the manufacturer's instructions:
The temperature was increased gradually to a peak of 1500 °C.
The total duration of the sintering cycle lasted between 8 and 9 hours, including a controlled, gradual cooling phase.
After complete crystallization, the final sintered crowns were ready for adaptation testing and mechanical examination.

Figure 3. Sample after sintering.

Fracture Resistance Testing. Compressive loading was conducted at room temperature using a computerized electronic universal testing machine (Model WDW-200E). The test was performed at a constant crosshead speed of [1 mm/min] in accordance with the ISO 6872 standard. The load and displacement data were continuously recorded until the specimen reached failure. The mechanical performance of the fabricated zirconia crowns was evaluated via compressive loading using a Universal Testing Machine (UTM, Model WDW-200E) under controlled parameters:

Figure 4. Universal testing machine (UTM).

Specimen Adaptation: Before testing, each zirconia crown was seated on its corresponding duplicate stone die to guarantee ideal stability and uniform adaptation.
Positioning: The assembly (die and crown) was centered on the lower rigid platform of the UTM to ensure strictly axial loading.
Loading Protocol: A custom-made metallic indenter with a rounded tip was aligned perpendicular to the exact center of the occlusal surface. This setup ensured uniform stress distribution, simulating clinical masticatory force application.
Testing Parameters: A vertical compressive load was applied continuously at a constant crosshead speed until a catastrophic fracture occurred. The load was monitored via UTM software to automatically record the maximum force at failure in Newtons (N).
Failure Analysis: Fracture was defined by a sudden drop in the load-displacement curve, accompanied by visible cracking or complete fragmentation of the crown.

Results

Following the tests, the fracture patterns were visually inspected, and the maximum load at fracture (N) was recorded. The collected data were subjected to statistical analysis. An independent samples t-test was performed to compare the mean fracture strength between Group A (Full Anatomy Cusp) and Group B (Flat Cusp). The significance level was set at $\alpha = 0.05$.
Fracture Resistance Measurements The descriptive statistics for the fracture resistance of both evaluated groups are summarized in Tables 1 and 2.
For the zirconia crowns with a full anatomy cusp (Group A), the fracture resistance values ranged from a minimum of 1903 N to a maximum of 2173 N, with a calculated mean value of 2063 N.
For the flat cusp zirconia crowns (Group B), the fracture resistance values ranged from a minimum of 1987 N to a maximum of 2125 N, with a calculated mean value of 2059 N.
The comparative statistical analysis between the two design groups is presented in Table 1. The independent samples t-test revealed a t-

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value of 0.12 with a corresponding p-value of 0.905. Since the p-value is greater than the established significance level (P > 0.05), the difference in fracture resistance between the full anatomy cusp group and the flat cusp group was not statistically significant. This statistical result indicates that the null hypothesis cannot be rejected, and the minor observed variations are likely due to chance (Figure 5).

Discussion

Zirconia exhibits high flexural strength and transformation toughening, which allows it to resist crack propagation under occlusal loading. These properties make zirconia highly suitable for CAD/CAM fabricated restorations, particularly in posterior regions where occlusal forces are high. In addition, advancements in CAD/CAM technology have enabled the fabrication of restorations with precise anatomy and standardized thickness, improving their clinical performance and durability [19].

In the present study, the fracture resistance values of the two occlusal surface designs (full anatomy occlusal surface and flat occlusal surface without anatomy) showed no statistically significant difference. This finding could be attributed to the inherent mechanical strength of monolithic zirconia and its ability to distribute occlusal forces effectively. When full-coverage restorations are utilized, the biomechanical behavior relies heavily on the bulk thickness of the material and its uniform seating on the underlying tooth structure, which helps optimize stress distribution under compressive loads. Previous research has indicated that when high-strength ceramic materials are used, the overall fracture resistance of restorations depends more on the material's intrinsic properties and thickness than on minor variations in occlusal surface morphology [19]. Similarly, a comparison of the fracture resistance of CAD/CAM restorations [20] with different designs showed that design variation alone did not significantly affect fracture resistance values, suggesting that modern monolithic zirconia can compensate for differences in restoration geometry, resulting in comparable mechanical performance between different designs.

Another important factor that may explain the comparable fracture resistance between the two groups is that the recorded fracture loads in most laboratory studies exceed the maximum physiological occlusal forces in the posterior region. Previous studies have reported that occlusal forces in the molar region typically range between 200 and 800 N, while fracture resistance values of ceramic occlusal veneers often exceed 2000 N. Therefore, both designs tested in the present study likely provided sufficient strength to withstand functional occlusal loads, which may explain the absence of statistically significant differences between them [21].

Based on these findings, it can be suggested that the occlusal surface design may not be the primary determinant of fracture resistance in CAD/CAM Zirconia-based ceramic restorations. Instead, factors such as material type, thickness of the restoration, adhesive bonding protocol, and the mechanical properties of the restorative material appear to play a more significant role in determining the overall fracture resistance of the restoration. This observation is consistent with previous systematic reviews that emphasized the importance of material selection and bonding quality rather than restoration design alone in determining the mechanical performance of occlusal veneers [19].

Conclusion

Modifying the occlusal design from anatomic to flat does not significantly affect the fracture resistance of monolithic zirconia crowns. Both designs demonstrated exceptional load-bearing capacities that comfortably exceeded maximum clinical masticatory forces. This suggests that other underlying variables, such as material intrinsic properties and thickness, may exert a more substantial influence on the mechanical durability of these restorations.

Suggestions for Future Research

Investigating the impact of various adhesive bonding agents and techniques on the overall fracture resistance of zirconia-based restorations.

Comparative Material Analysis

Conducting a comparative study of diverse restorative materials under identical preparation parameters to isolate material-specific mechanical behaviors.

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Table 1. Statistical comparison of fracture resistance between groups.

Sample	Valid	Mean	S.E	S.D	Minimum	Maximum	T-test	P-value
Full	20	2063	28.29	89.47	1903	2173	0.12	0.905
Flat	20	2059	17.4	55.01	1987	2125		

Figure 5. Graphical distribution of the mean fracture resistance across the tested groups.