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Article

Comparative Fracture Resistance Analysis of Translucent Monolithic Zirconia Dioxide Milled in a CAD/CAM System

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Abstract: The aim of this study was to evaluate and compare the fracture resistance of definitive zirconia dioxide restorations obtained using a computer-aided design and manufacturing (CAD/CAM) system. Methods: Two groups of ten samples were analyzed for each material (n: 20); the first group was Zolid Gen X Amann Girrbach (ZGX) and the second group was Cercon HT Dentsply Sirona (CDS). The restorations were designed with identical parameters and milled with a CAD/CAM system. Each specimen was load tested at a speed of 0.5 mm/min, with a direction parallel to the major axis of the tooth and with an initial preload of 10 N until fracture using a universal testing machine (Universal/Tensile Testing Machine, Autograph AGS-X Series) equipped with a 20 kN load cell. The results obtained were recorded in Newtons (N), using software connected to the testing machine. Results: Statistically significant differences were found, and the fracture resistance of the monolithic zirconia crowns was lower in the CDS group (1744.84 ± 172.8 N) compared to the ZGX group (2387.41 ± 516 N). Conclusions: The monolithic zirconia CAD-CAM zirconia crowns showed sufficient fracture resistance when used in posterior molar and premolar zones with either material, as they withstood fracture loads greater than the maximum masticatory force.

Keywords: zirconia; monolithic; multilayer zirconia; fracture resistance; CAD/CAM materials

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1. Introduction

In dentistry, the introduction of technological advances such as digital work flow and CAD/CAM (computer-aided design/computer-aided manufacturing) systems have enabled the fabrication of fixed dental prostheses using ceramic blocks [1]. CAD/CAM blocks were introduced in the dental market in 1980 [2], while the production of restorations using zirconia blocks started in the late 1990s [3].

After the production and purification process, pure zirconia can be presented in three phases due to its chemical structure: monoclinic, tetragonal and cubic. The cubic phase crystallizes at a temperature of 2680 °C, and transforms at 2370 °C into the tetragonal phase. At a temperature of 1170 °C it transforms to monoclinic, with a volume increase of approximately 4–5%. The addition of yttrium oxide leads to the formation of the metastable tetragonal phase and also of the cubic portions of the structure, simultaneously, maintaining the stability of the crystalline form at room temperature [4,5]. Thus, the different generations from yttria-stabilized tetragonal zirconia oxide (Y-TZP) appear: The first generation, 3Y-TZP, contains 3% in moles of yttrium and 0.25% in weight of aluminum oxide, being a more robust material, with a bending strength of up to 1200 MPa. The second generation, 3Y-TZP 3% in moles of yttrium and 0.05 wt.% of aluminum oxide, was created with the purpose of improving translucency, reducing the alumina content of the first generation; however, it was not yet suitable for aesthetic areas, having to be layered with ceramic [6].

In 2015, a new ceramic system was introduced to the market: the tetragonal zirconia polycrystal stabilized with 5% moles of yttrium improving translucency, thus developing the third generation of 5Y-TZP. Its cubic phase reached approximately 50% of the structure, and the size and number of crystals, which are larger than 3Y-TZP, favor light transmission, reducing the refraction effect and giving better translucency with better optical properties, but with lower fracture resistance. In 2017, the fourth generation appeared, containing tetragonal zirconia polycrystals stabilized with 4% moles of yttrium, increasing fracture resistance compared to the third generation and with higher translucency than the first generation [7]. In general, it has been stated that increasing the yttrium content increases the translucency of the material but decreases the flexural strength of zirconia [8,9].

Improved mechanical properties, biocompatibility and greater resistance to corrosion are advantages of zirconia. Its challenge is to present esthetics similar to natural dentition [10]. Currently, monolithic translucent zirconia merges fracture resistance and color enhancement [11], evolving from an original white and opaque appearance to translucent, chromatic and polychromatic (multilayer) forms, which combine the favorable properties of different zirconia generations (3Y-TZP, 4Y-TZP and 5Y-TZP) [12]. Lately, the development of new materials, including the introduction of new products that decrease the amount of zirconium dioxide, doped in the form of calcium phosphates, can further improve the mechanical properties and could be a promising option. They have been categorized within this type of zirconium materials, which is worth mentioning although they have not been analyzed in this study [13].

Monolithic zirconia restorations became popular with the development of new CAD/CAM technologies [14,15]. It appears that monolithic translucent restorations improve survival compared to porcelain veneers with lower fracture resistance. It is a simplified procedure to make monolithic total coronal restoration, and it is the first choice compared to layered restorations avoiding the risk of chipping [16]. In addition, the mechanical properties of monolithic zirconia materials are superior to those of all-ceramic restorative materials [4]. In in vitro studies, monolithic zirconia single crowns showed a higher fracture resistance than layered zirconia crowns and could withstand the stresses that occur in the molar region during mastication (between 441 and 981 N) [17,18].

Zirconia restorations can be milled in a fully sintered state (hard-state material) or pre-sintered (soft-state material) [19]. In addition, high-speed sintering allows the production of zirconia restorations in a single appointment using a chairside workflow. These new rapid sintering protocols do not show a negative influence on flexural strength [20]. After milling, zirconia prostheses should be sintered to achieve higher density and maximum strength [21,22].

Monolithic Zirconia

The first multilayer monolithic zirconia system had the same yttrium content and cubic fraction in the different layers of the material, with the only difference in the pigment composition, which caused differences in shade, but not in translucency [23]. Modifications in composition, structure and fabrication method have resulted in multilayered and pre-colored monolithic zirconia discs considered universal, with a balance between flexural strength and translucency, presenting a wider range of indications for single anterior and posterior crowns up to plural fixed prostheses. The most versatile combination was achieved using 4Y-TZP (fourth generation zirconia), with a more intense chroma in the base or cervical layer and 5Y-TZP (third generation zirconia) being more translucent in the upper or incisal layer [24].

Monolithic zirconia dioxide can be presented with various types of translucency, including low, medium, high, super and ultra, achieving the different gradients of color and translucency desired for each clinical case. The grain size influences these translucent presentations and grains up to 80 nm result in a translucency similar to dental porcelains [25].

Therefore, monolithic zirconia minimizes the risk of restoration failure due to chipping and incompatibility between the veneering ceramic and the zirconia ceramic [26].

1.1. Zirconia Cercon HT Dentsply-Sirona (CDS)

According to its manufacturer, because of its mechanical and esthetic properties CDS can be applied in multi-unit crowns and bridges with a maximum of two pontics between stacked crowns in anterior and posterior regions. It is composed of yttrium-stabilized zirconia (Y-TPZ). It can be used as a fully anatomical restoration, or as a framework to be veneered with feldspathic ceramics. Due to their composition (Table 1), it has high strength, corrosion resistance, biological compatibility and translucency [27].

Table 1. Composition of multilayer monolithic zirconia dioxide (CDS-ZGX).

Materials	Components	%
CDS	$ZrO_2 + HfO_2 + Y_2O_3$	≥94.0%
	Y_2O_3	5%
	Al_2O_3	≤1%
	Fe_2O_3	≤0.01%
	Other oxides	≤0.2%
ZGX	$ZrO_2 + HfO_2 + Y_2O_3$	≥99.0%
	Y_2O_3	6–7%
	Al_2O_3	≤0.5%
	Fe_2O_3	≤0.5%
	Other oxides	≤0.1%

1.2. Zirconia Solid Gen-X Amann Girrbach (ZGX)

This is a highly translucent and highly resistant multilayer monolithic zirconia oxide material, with a chromatic transition that improves its efficiency and esthetics, blending well with natural teeth. It is virtually divided into four horizontal layers to adapt perfectly to the color gradient, simplifying the choice of material for its multiple indications, such as fully anatomical crowns and bridges from four pieces and anatomically reduced crown structures (Table 1).

Monolithic zirconia has been continuously developing, and it is necessary to know properties such as the fracture resistance of these new materials. Compared to other ceramic materials, monolithic zirconia significantly reduces the space required for the preparation of the restoration and, therefore, contributes to a prosthetic restoration that preserves the greatest amount of tooth structure [19]. Therefore, the objectives of this research were to evaluate and compare the fracture resistance of two CAD-CAM materials, zirconia dioxide CDS and ZGX, stating as the null hypothesis that there would be no significant differences in fracture resistance between the zirconia dioxide restorations studied.

2. Materials and Methods

2.1. Materials

Two translucent monolithic zirconia dioxide materials (CDS and ZGX) were selected. A typodont was used with a preparation to make a full crown, following the following parameters: 2 mm occlusal reduction, 1.0 mm axial reduction, chamfered termination line, parallelism between axial walls of 6 degrees and rounded edges. A digital file of the preparation was obtained with a high power structured light scanner (PrimeScan^{TM}, Dentsply-Sirona ^{TM}, New York, NY, USA).

2.2. Digitalization of the Model and Design

Once the model had been digitized, the restoration was designed in integrated design software (InLAB SW 22.0, Dentsply-Sirona^{TM}, Bensheim, Germany) (Figure 1). For milling, the information was transferred to an integrated milling machine (CEREC InLab MCXL^{TM}, York, PA, USA). Twenty restorations were made in two groups of ten specimens for each material (Figure 2).

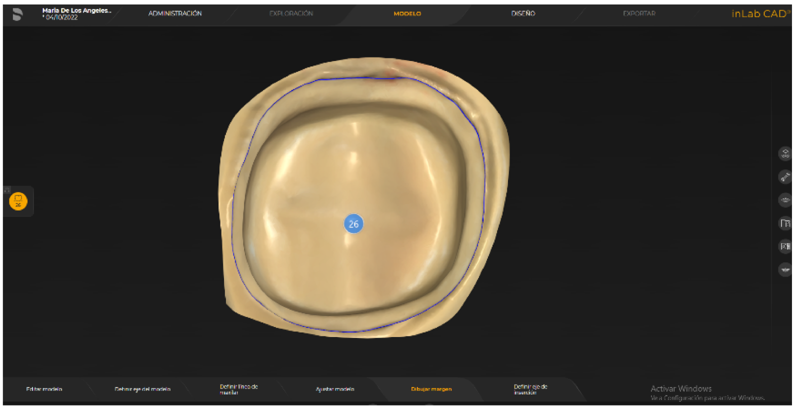


Figure 1. Digitization of the model of tooth 26.

Figure 2. Restorations on CAD-CAM disks of zirconia dioxide before sintering.

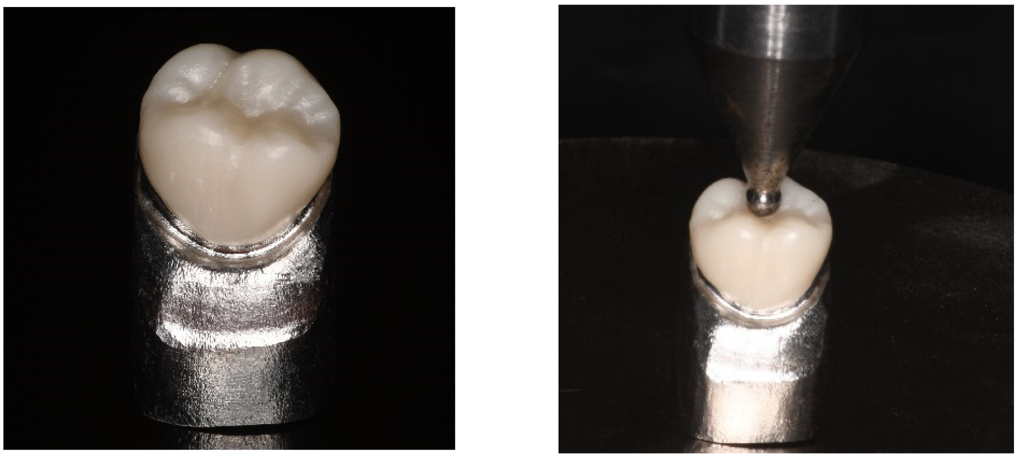
2.3. Sinterization

Sintering of the zirconia dioxide restorations was carried out in a slow sintering furnace (CEREC SpeedFire, Dentsply-Sirona, Bensheim, Germany) with a sintering time of 8 h at a maximum temperature of 1500 °C on a preset program for the material.

2.4. Fracture Test

A cast metal master die (Figure 3a) was obtained from the initial scan of the original dowel type, suitable for load testing, for the manufacture of the metallic die; it was made by scanning, and once the digital model was obtained it was milled in wax. Later, it was cast with a nickel-chromium casting alloy, without beryllium. The specimens were supported with a non-cemented metal die and placed on the platform of the universal testing machine (Universal/Tensile Testing Machine, Autograph AGS-X Series).

The specimen was load-tested at a rate of 0.5 mm/min, with a direction parallel to the major axis of the tooth, with an initial preload of 10 N (Figure 3b) equipped with a 20 kN load cell. The load was applied through a hardened steel pilot punch with a radius of 3 mm applied in the central pit of the crown until fracture occurred. The force/displacement values of the specimens were determined using the built-in software (TRAPEZIUM LITE X-V for Windows 10 Software). The results were expressed in newtons (N).



(**a**) (**b**)

Figure 3. (**a**) Master die in cast metal. (**b**) Load of the punch in tempered steel on the sample seated in the cast metal die.

2.5. Evaluation of the Fracture Mode

The fracture surface of the samples after loading was observed and analyzed using a high-resolution stereomicroscope (Olympus; SZX7, Tokyo, Japan).

3. Results

3.1. Descriptive Analysis

Table 2 shows the descriptive statistics of the fracture resistance of materials used in this study.

Table 2. Descriptive statistics of the fracture resistance.

CAD/CAM Material	Media (SD)	CI 95%	CV	Minimum	Maximum
CDS	1744.84 (172.80)	(1628.75;1860.93)	9.9%	1394.60	1563.50
ZGX	2387.41 (516.10)	(2018.23;2756.59)	21.6%	1966.50	3113.50

Note: Fracture strength expressed in Newtons. SD: standard deviation, CI: Confidence interval, CV: coefficient of variation.

The ZGX material showed a higher average fracture resistance, with 2387.41 (SD = 516.10) N; the 95% confidence interval for the mean was (2018.23–2756.59) N, and the coefficient of variation value indicated a mean dispersion (CV = 21.9%), with a minimum and maximum strength of 1966.50 N and 3113.50 N, respectively. In comparison, the values reported with the CDS material yielded a lower average fracture resistance with 1744.84 (SD = 172.80) N, where the 95% confidence interval for the mean was (1628.75–1860.93) N, the dispersion was low (CV = 9.9%) and the observations were between Min = 1394.60 N and Max = 1563.50 N (Table 2). Figure 4 shows the quartiles, maximum and minimum values. From the comparison, it was observed that the maximum value reached with the CDS material was lower than Quartile 1 (25%) of ZGX, showing a higher resistance.

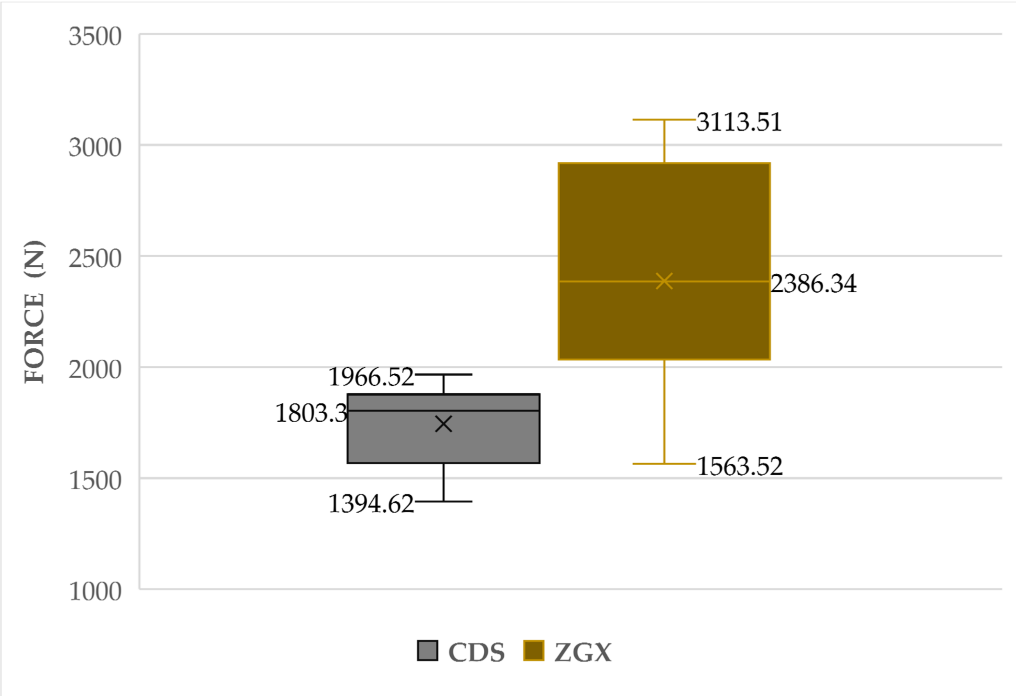


Figure 4. Box and whisker diagram for fracture resistance of CAD/CAM materials in zirconia dioxide.

Figure 5 shows the average fracture resistance of the materials. ZGX presented higher values than CDS.

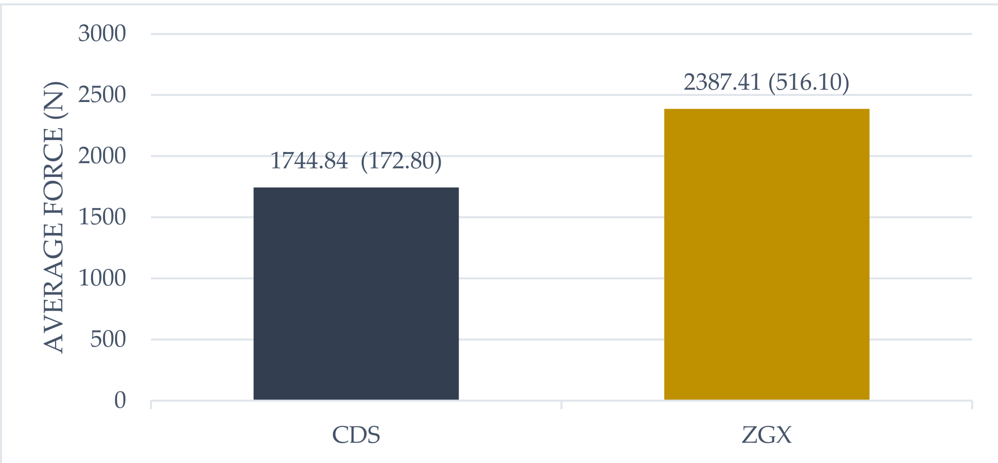


Figure 5. Bar chart for the average fracture strength of CAD/CAM materials in zirconia dioxide.

3.2. Inferential Analysis

With the results in Table 3, the null hypothesis that the fracture resistance measurements are normally distributed was not rejected, with the Shapiro–Wilk statistic (p-value > 0.05), and the null hypothesis of equality of variances (p-value < 0.05) was rejected by Levene's test. Consequently, to evaluate the research hypothesis, the parametric test was used, with Student's t-statistic for independent samples assuming different variances.

Table 3. Normality and Levene's test (verification of assumptions).

CAD/CAM Material	Shapiro–Wilk			Levene	
	Statistic	gl	*p*-Value	F	*p*-Value
CDS	0.92	10	0.33	7.15	0.02
ZGX	0.95	9	0.71		

Note: Significance level 5%. **gl**: degrees of freedom. **F**: test statistic following a Fisher distribution. ***p*-value**: probability of rejecting the null hypothesis.

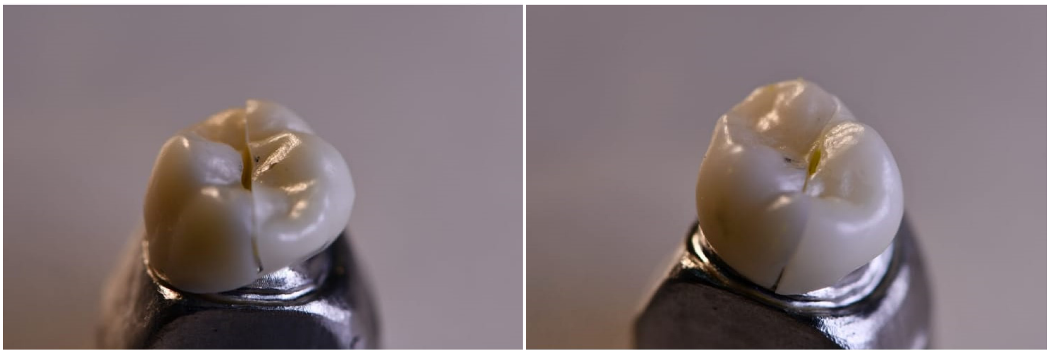
According to Table 4, the null hypothesis was not accepted (t = −3.75, *p*-value = 0.003 < 0.05). It was then determined, with a significance level of 5%, that there were significant differences between CDS and ZGX.

Table 4. Descriptive statistics of fracture resistance of CAD/CAM materials in zirconia dioxide.

CAD/CAM Material	Media (DE)	Statistical T-de Student	*p*-Value
CDS	1744.84 (172.80)	−3.75	0.003 < 0.05
ZGX	2387.41 (516.10)		

Note: Significance level 5%, Average testing for independent samples. DE: Standard deviation.

From the fractographic analysis, it can be observed that the two materials under study presented a brittle fracture. Once the critical stress value has been reached, brittle materials present unstable cracks, that is, they do not require an increase in stress for the spontaneous propagation of the crack, and catastrophic failure occurs (Figure 6).



(**a**) (**b**)

Figure 6. Images of the fracture surfaces of the different materials studied: (**a**) CDS; (**b**) ZGX.

4. Discussion

The all-ceramic crown is a common restorative method for a tooth that has lost much of its structure [28]. Compared with the metal–ceramic crown, it has excellent biocompatibility and esthetic appearance, magnetic resonance imaging compatibility, and superior refractive index and transparency [29]. Currently, materials used in all-ceramic crowns include mainly feldspathic, silica-based and yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) ceramics [30]. Full-contour zirconia restorations are gaining popularity in the market, at the expense of multilayer systems [31]. CAD/CAM applications offer a standardized fabrication process with a reliable and predictable workflow for single and complex restorations on teeth [32]. Monolithic zirconia crowns have high flexural strength and fracture resistance [33]. Mechanical properties such as fracture resistance would be affected by the different composition of each material. However, if these properties exceed the masticatory forces, they are clinically favorable for application in the posterior sector. Therefore, materials such as zirconium dioxide, with high resistance due to their fully crystalline microstructure and thanks to the presence of a resistive transformation mechanism, exhibit superior fracture resistance values in relation to other ceramic materials by preventing fracture propagation [34].

Therefore, the objective of this research was to compare, through an in vitro study, the fracture resistance of zirconium oxide crowns of two different commercial brands (CDS and ZGX). The null hypothesis was rejected, and it was concluded that there are differences in the average fracture resistance between both CAD/CAM materials. In addition, mean fracture strengths of 1744.84 ± 172.8 N were observed for CDS, and a higher strength of 2387.41 ± 516.1 N for ZGX. This differs from those reported in a study, where they compared the fracture load of four brands of zirconia, whose reported mean fracture loads were 4804.94 ± 70.12 N, 3317.76 ± 199.80 N, 3086.54 ± 441.74 N and 2921.87 ± 349.67 N for Cercon HT, Cercon XT, Zolid Gen X and Vita YZ XT, respectively; the crowns were sandblasted before cementing to increase bond strength. Zolid Gen X had the most cracks overall, while Cercon HT crowns had the fewest cracks. It was concluded that Cercon HT presented the best strength properties, the highest fracture load and no visible cracks, and that Zolid Gen X presented the lowest strength properties [35]. In contrast to our study, the crowns were not cemented; in a study by Sorrentino et al., who cemented the restorations with a dual-curing self-adhesive universal resin cement to simulate a real clinical situation, the formation of an adhesive layer probably contributed to an increase in the fracture resistance, allowing the cement to act as an elastic stress adsorbent and compensating for the stiffness of the zirconia core; this could strengthen the restoration, allowing occlusal loads to be dissipated over the entire surface of the crowns [36]. Cementation was not carried out, because this study clearly focuses on the fracture resistance of the material, but not with a cementation process, since the values change.

Bulut, in his study, concluded that the occlusal thickness and the type of cement significantly affected the fracture resistance of the crowns, but the occlusal thickness was more significant. Samples of 0.5, 1.0 and 1.5 mm were made, and the 1.5 mm crowns cemented with a resin cement showed higher fracture resistance compared to the other thicknesses; however, no significant differences were found, and therefore posterior zirconia crowns can withstand physiological occlusal forces even with a thickness as low as 0.5 mm [37]. Corroborating with this, Sorrentino et al. similarly suggested that the occlusal thickness could be reduced to 0.5 mm without affecting the fracture resistance; the crowns exhibited a high fracture resistance at this 0.5 mm thickness, with a fracture load of 1400 N being clinically acceptable. In a literature review on zirconium dioxide-based restorations, the results showed a performance similar to that of this study in terms of fracture resistance, it being a resistant material suitable for this purpose in areas with high functional load, and also fulfilling the esthetic requirements of the patient [38].

An important aspect to mention is that the production of the restorations in this study involved several stages such as milling and sintering, and therefore some certain self-reported limitations of the material, such as the production of the restorations involving several processing steps, could cause defects in the finished product [39]. Therefore, there are currently studies that analyze whether variables in the production process could affect the clinical success of monolithic zirconia crowns [40–42].

An in vitro study by Kauling [43] evaluated the properties of three-unit zirconia monolithic fixed dental prostheses (FPD) after rapid sintering and compared the properties with conventional sintering. They found that the fast-sintering FPDs had a better marginal and occlusal fit than the conventionally sintered FPDs. In addition, no significant differences in fracture load values were found due to the sintering procedure, but artificial aging was found to significantly affect the fracture load values. In general, fast sintering FPDs had equal and better values for fracture set and fracture load than conventional sintering FPDs. However, other authors concluded that there was no significant difference between the two groups, and the mechanical strength of the material was not affected, which would imply clinical and laboratory time savings when performing rapid sintering on translucent monolithic zirconium dioxide restorations. However, rapidly sintered restorations have limited reliability, depending on the case [44].

In another study, the flexural strengths of different kinds of multilayered zirconia in enamel and dentin layers was evaluated. The strength was similar for that of both layers, and the multilayer restoration accumulated the highest strength, followed by the translucent super multilayer and the ultra-translucent multilayer. However, the strength of the transverse multilayer was lower than that of the enamel or dentin layers due to weak interfaces. In addition, it was mentioned that, when measuring strength by bending, there may be errors due to friction and accuracy in determining the distances of the loading spans [45]. The result of resistance to fracture shown with CDS in this research was similar to that obtained in a study where they compared the resistance to fracture between a group of crowns made to measure and a group of prefabricated crowns, both made of Cercon HT Dentsply-Sirona Zirconia [34], yielding an average resistance of 1987.38 ± 414.88 N for the crowns made to measure and 1793.54 ± 423.82 N for the prefabricated ones, finding no significant differences between the two. According to the Canadian Agency for Drugs and Technologies in Health (Ottawa), the average resistance to the initial fracture shown with Zolid Gen-X was 2634 ± 106.2 N, and after aging in a chewing simulator it was 2087 ± 126.1 N, showing similar values to those reported in the present investigation, in Table 5 [27,34].

Table 5. Comparison of the fracture resistance of CAD/CAM materials in zirconia dioxide: CDS (Cercon Dentsply Sirona); ZGX (Zolid Gen-X Amann Girrbach).

Materials	Results	
CDS	Abad C. 1744.84 ± 172.80 N	Kongkiatkamon S. 1987.38 ± 414.88 N
ZGX	Abad C. 2387.41 ± 516.10 N	Ottawa 2634 ± 106.20 N

It should be noted that, during the load test that was performed in the first instance, a printed resin die was used and during the process the initial failure was of the die, so it was decided to perform the test in a more resistant material. In this case, a cast metal cobalt-chromium die with a higher elastic modulus and fracture resistance was used; however, a natural tooth could have replicated the clinical environment more accurately if it had been chosen as an abutment. On the other hand, natural teeth have different sizes, shapes and qualities, and therefore the preparation material would be difficult to standardize [46].

Laboratory tests apply static loads until the material breaks by means of a universal machine, representing its behavior in a force-displacement curve and recording the maximum load applied. These tests provide information on the strength of the material, the potential risk of failure and the deformation of the material. However, they cannot sufficiently predict the long-term performance of dental restorations. Badawy et al. [47] mentioned in their study the importance of knowing the fracture resistance of dental ceramics, which by nature are brittle and have an increased susceptibility to fracture under stress. A restorative material with high fracture resistance presents better fracture resistance and longevity. As an in vitro study, one of the limitations of this research is that the behavior of these materials under cyclic fatigue was not analyzed. Fracture resistance testing, using a single unidirectional compressive load, provides only limited insights into clinically relevant mechanisms of crown damage under forces with different directions and cyclic loading [43]. Future research needs to analyze the cyclic fatigue and clinical behavior of this material over time, as well as to analyze the material cemented with different adhesive techniques. Therefore, experimental settings that reproduce situations similar to intraoral conditions are needed. More evidence from long-term clinical studies is needed to verify the fracture performance of monolithic zirconia CAD/CAM materials for indirect full-coverage restorations.

5. Conclusions

- Although it was found that the ZGX material obtained higher fracture resistance compared with the CDS; the crown fracture loads of the two materials were in the acceptable range.
- The monolithic zirconia CAD-CAM zirconia crowns showed sufficient fracture resistance when used in posterior molar and premolar zones with either material, as they withstood fracture loads greater than the maximum masticatory force.

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