

Original Research Article

Effect of Selective Grinding Methods on Fracture Toughness of Monolithic Zirconia with Different Translucency: A FEA Study

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ABSTRACT

Aim: Chairside and laboratory grinding procedures are frequently required to optimize the fit and occlusion of zirconia restorations; however, these adjustments may introduce surface defects, trigger phase transformation, and adversely affect long-term mechanical performance. The influence of clinically relevant grinding parameters on different zirconia generations remains unclear. This study aimed to evaluate the tribomechanical behavior of 3Y-TZP, 4Y-PSZ, and 5Y-PSZ under simulated milling conditions.

Materials and Methods: CAD models of mandibular first molar crowns (1.5 mm thickness) were generated and analyzed using finite element analysis with the Explicit Dynamics module in ANSYS Workbench 2022 R2. A 1.0-mm milling bur was modeled as a rigid body, and rotational speeds ranging from 200000 to 400000 RPM were simulated. Zirconia materials were defined as linear isotropic elastic solids. Wet and dry grinding conditions were represented by friction coefficients of 0.15 and 0.45, respectively. Structural reliability was assessed using Weibull statistics.

Results: Dry milling significantly increased stress magnitudes (820–960 MPa), resulting in fracture probabilities of up to 77% for 5Y-PSZ. Wet milling substantially reduced stresses (520–620 MPa) across all zirconia types. A rotational speed of 350000 RPM minimized vibrational instability.

Conclusion: Wet grinding is critical for preserving the mechanical integrity of high-translucency zirconia. Among the materials tested, 3Y-TZP demonstrated superior fracture toughness under high-stress conditions.

Keywords: Dental high-speed technique; Dental stress analysis; Finite element analysis; Zirconium oxide

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INTRODUCTION

In recent years, the growing demand for high-aesthetic dental restorations has driven the transition from metal-ceramic to all-ceramic systems.^{1,2} Among these, zirconia-based ceramics have gained prominence due to their favorable biocompatibility, high mechanical strength, and low bacterial adhesion.³ Particularly, yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) are widely used in fixed prosthodontics as both core and monolithic restorative materials, facilitated by the development of CAD/CAM technologies.⁴

Conventional veneered zirconia restorations often suffer from porcelain chipping at the veneer–core interface, compromising their longevity.⁵ Monolithic zirconia restorations were introduced to address this complication by eliminating the veneering layer, thereby enhancing mechanical durability and simplifying clinical procedures.⁶ However, mechanical adjustments, such as grinding and polishing during clinical or laboratory adaptation, can induce surface defects, trigger tetragonal-to-monoclinic phase transformation, and reduce the long-term strength of zirconia.^{7,8}

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The optical and mechanical properties of zirconia have been further optimized through the development of new generations of zirconia with varying yttria content, such as 3Y-TZP, 4Y-PSZ, and 5Y-PSZ.⁹ These materials differ in their translucency and fracture toughness, influencing their clinical indications.^{9,10} Understanding how surface modification parameters such as rotational speed, and the presence of coolant, affect the mechanical performance of these zirconia materials is crucial for optimizing restorative outcomes.^{7, 8}

This study aims to evaluate the mechanical response of different generations of monolithic zirconia (3Y-TZP, 4Y-PSZ, and 5Y-PSZ) under various clinical grinding conditions using finite element analysis (FEA), focusing on the effects of coolant application (wet vs. dry conditions), rotational speed (rpm) and zirconia translucency level. It was hypothesized that 3Y-TZP would exhibit greater fracture toughness to grinding-induced stress and fracture compared to 4Y-PSZ and 5Y-PSZ due to its higher tetragonal phase stability, that wet grinding conditions would result in more favorable stress distribution and higher fracture toughness than dry conditions by reducing frictional heat accumulation and minimizing thermally induced microstructural damage, and that increasing rotational speed would lead to greater stress concentration within the zirconia structure. The findings are expected to provide insights into optimal clinical adjustment protocols that minimize stress concentration and preserve the structural integrity of zirconia restorations.

MATERIALS AND METHODS

This study was conducted to evaluate the mechanical stress response of monolithic zirconia ceramics during high-speed milling using the Explicit Dynamics module within the ANSYS WorkBench 2022 R2 (ANSYS Inc., Canonsburg, PA, USA) Finite Element Analysis (FEA) platform. Three-dimensional (3D) crown models, specifically a simplified geometry representing the mandibular first molar and maintaining a block thickness of 1.5 mm, were generated using CATIA V5 (Dassault Systèmes, Vélizy-Villacoublay, France) software. This simplification focused the analysis on the zirconia material's mechanical reaction while maintaining computational efficiency (Fig.1A-B).

Three distinct zirconia materials from the same manufacturer were selected based on their varying translucency levels: KATANA Zirconia HTML (3Y-TZP), STML (4Y-PSZ), and UTML (5Y-PSZ) (Kuraray Noritake, Tokyo, Japan). A single 1.0 mm diameter bur geometry was employed in the simulation (Fig.2). To streamline calculations and maintain focus on the stress distribution within the zirconia, the milling bur was idealized as a Rigid Body, neglecting the bur's material-specific deformation. However, four distinct rotational speeds, representative of common clinical practice with dental micromotors and high-speed air turbines, were defined: 200000 RPM, 300000 RPM, 350000 RPM, and 400000 RPM.

Zirconia, being a brittle material, exhibits a linear elastic response until the point of fracture. Accordingly, the material behavior was defined using the

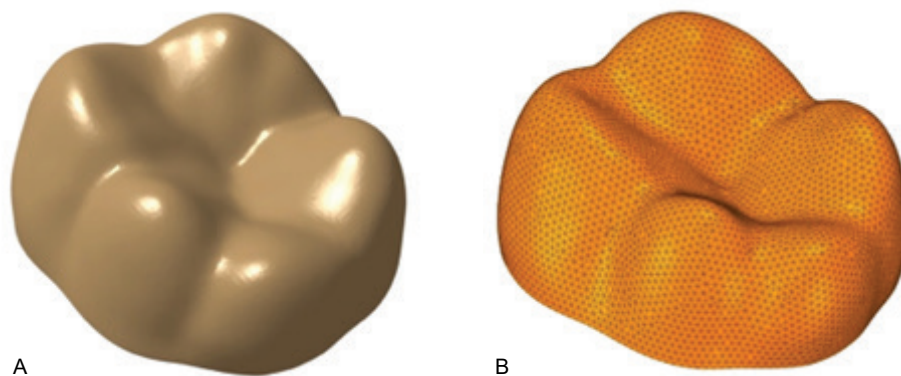


Figure 1. Mandibular first molar; A, crown model. B, mesh image.

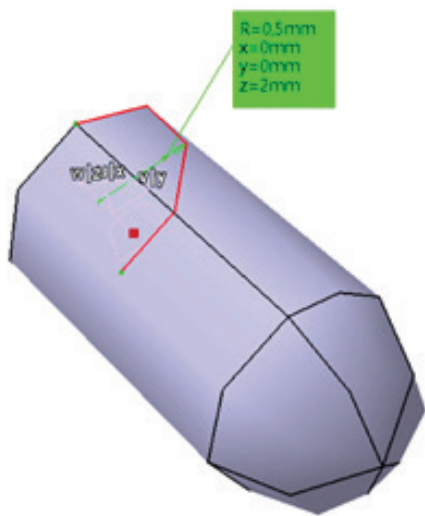


Figure 2. 1.0 mm radius chamfer bur point CAD model

Linear Isotropic Elastic Model based on Hooke’s Law principles, requiring the definition of Elastic Modulus, Poisson’s Ratio, and Density. Since the fracture behavior of brittle materials is governed by a stochastic process dependent on the size and distribution of critical flaws within the material volume, rather than a deterministic strength threshold, the structural reliability and probability of failure (PoF) of the zirconia specimens were characterized using a two-parameter Weibull distribution function based on the weakest link principle. This model is defined by two parameters: the characteristic strength, representing the stress level at which specimen failure is expected, and the unitless Weibull Modulus, which reflects the scatter of strength data and thus the homogeneity of the flaw population within the materi-

al. Accordingly, rather than relying on a single peak stress value, the stress values and corresponding volumes of all elements within the finite element mesh were individually considered, and the cumulative probability of fracture was calculated for each specimen using Weibull statistics. This statistical approach allowed for the calculation of cumulative fracture probability across the finite element mesh, rather than relying solely on a deterministic maximum stress value. Material properties were defined according to the manufacturer’s data and previous report (Table 1).¹¹

The mechanical effects of the clinical environment were incorporated by simulating wet and dry milling conditions. These conditions were modeled through the variation of the Coefficient of Friction (COF), independent of thermal analysis:

Wet Milling: A COF of $\mu=0.15$ was adopted, representing the lubricating and chip-evacuating effect of the coolant, which minimizes direct contact and friction.

Dry Milling: A higher COF of $\mu=0.45$ was utilized, reflecting the aggressive dry-sliding mechanisms and increased friction resistance observed at the tool-material interface in the absence of coolant.

The use of the Explicit Dynamics solver was chosen for its solution stability and precise time-step management, which is critical for accurately modeling high-velocity, short-duration impact, and complex contact interactions inherent in high-speed milling.

Table 1. Parameters for Zirconia Blocks¹¹

Category	Properties	3Y-TZP	4Y-PSZ	5Y-PSZ	Unit
Density	Density	6080	6060	6050	kg/m ³
Elastic	Young’s Modulus	2.1e+05	2.05e+05	2.00e+05	MPa
	Poisson’s Ratio	0.300	0.310	0.320	-
	Bulk Modulus	1.75e+05	1.79e+05	1.85e+05	MPa
	Shear Modulus	80769	78244	75757	MPa
Weibull	Characteristic Strenght	837.41	415.37	318.50	MPa
	Weibull Modulus	8.96	6.03	5.76	-

kg/m³: Kilograms per Cubic Meter
MPa: Megapascal

RESULTS

The Explicit Dynamics analysis demonstrated a critical and complex interaction between material properties, tribological conditions, and rotational speed on the mechanical response of monolithic zirconia ceramics. Quantitatively, the simulations confirmed the generation of extremely high maximum contact stresses, peaking at 960 MPa on the zirconia surface. These peak stress magnitudes and the resultant probability of failure (PoF) were overwhelmingly governed by the milling environment (Fig. 3, Fig. 4).

Across all simulated conditions, maximum contact stress values ranged from 526.6 MPa (lowest, recorded under wet milling at 300,000 RPM) to 963.7 MPa (highest, recorded under dry milling at 300,000 RPM), while the corresponding probability of failure ranged from as low as 0.00% (3Y-TZP under wet conditions) to as high as 77.28% (5Y-PSZ under dry conditions at 200,000 RPM)

The study established a critical non-linear relationship between Rotational Speed (RPM) and mechanical risk, particularly evident in dry milling scenarios.

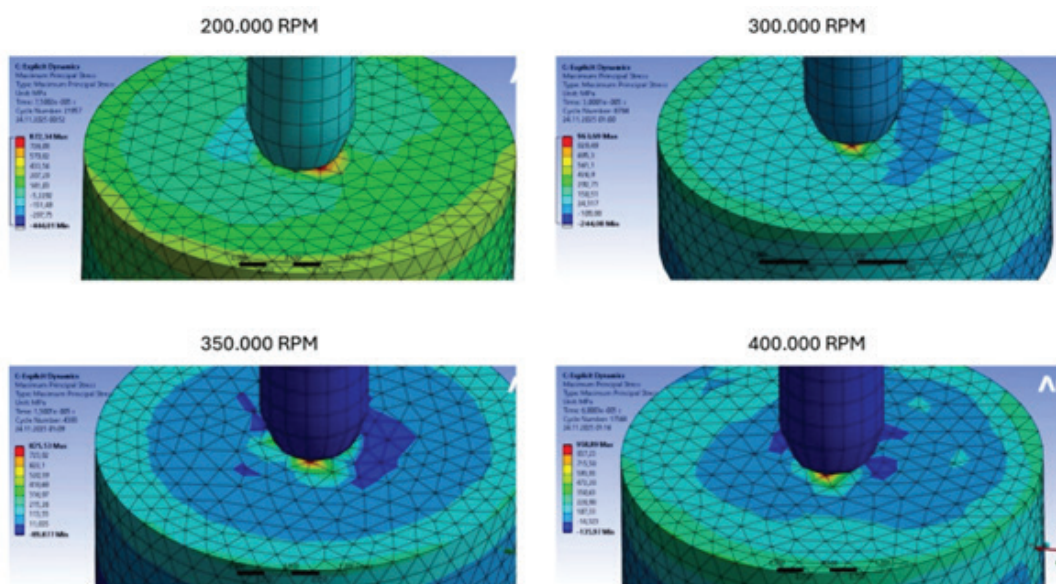


Figure 3. Maximum principal stress analysis at 200.000 RPM, 300.000 RPM, 350.000 RPM and 400.000 RPM in dry conditions

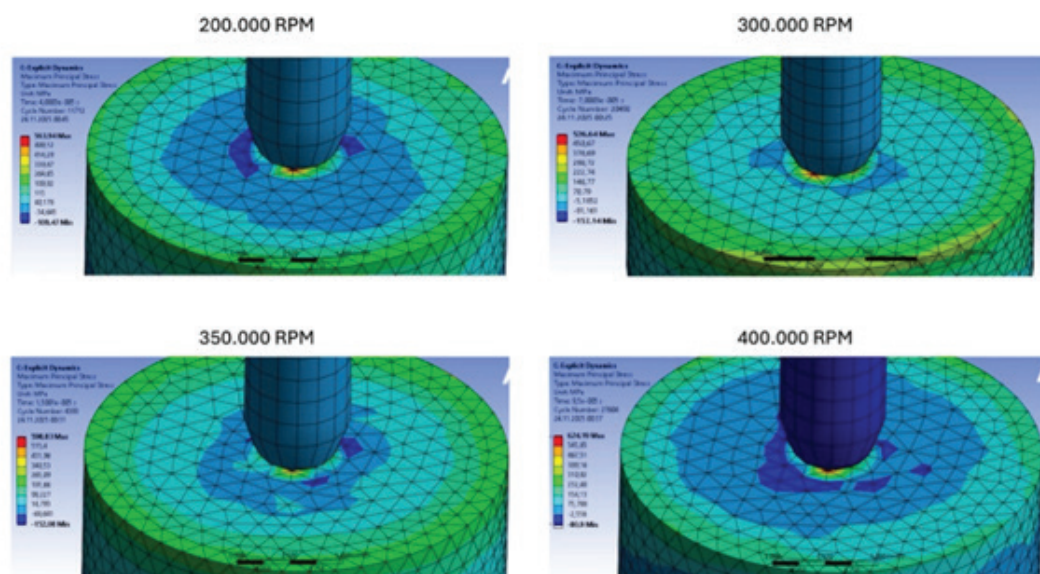


Figure 4. Maximum principal stress analysis at 200.000 RPM, 300.000 RPM, 350.000 RPM and 400.000 RPM in wet conditions

Low speeds of 200000 RPM induced high risk (77.28% PoF with 872 MPa stress) because the insufficient cutting velocity favored an inefficient dragging/tearing mechanism over clean cutting. Conversely, high speeds like 400000 RPM also led to high risk (70.54% PoF with 958 MPa stress) due to the amplification of inertial and impact forces. Crucially, 350000 RPM was identified as the Optimum Safe Point (lowest risk at 47.48% PoF with 825 MPa stress), where cutting dynamics were stabilized; this behavior is attributed to operating within a favorable stability lobe where vibrations and energy expenditure are minimized.

Furthermore, wet milling, defined by a lower coefficient of Friction ($\mu=0.15$), effectively mitigated risk by

confining the maximum stresses to a manageable range of 520–620 MPa; this coolant effect kept the PoF for the structurally sensitive 5Y-PSZ material within an acceptable 9%–15% range. Conversely, dry milling, characterized by increased friction, dramatically escalated the stress levels to between 820 MPa and 960 MPa. This rapid escalation in mechanical loading resulted in a catastrophic PoF surge up to 77% for 5Y-PSZ, confirming that the absence of lubrication and cooling constitutes a critical failure risk for high-translucency zirconias. Concurrently, the material hierarchy remained consistent across conditions, with the high-toughness 3Y-TZP maintaining integrity ($\text{PoF} < 1\%$), while the lower-rigidity 5Y-PSZ proved most vulnerable (Table 2, Table 3).

Table 2. Weibull analysis for dry conditions

Speed	Material	Maximum Simulation Stress	m	Sigma0	R0 (risk)	PoF (%)
200.000 RPM	5Y-PSZ	872.34 MPa	5.76	318.50	1.4818	77.28%
	4Y-PSZ	872.34 MPa	6.03	415.37	0.3526	29.72%
	3Y-TZP	872.34 MPa	8.96	837.41	0.0034	0.34%
300.000 RPM	5Y-PSZ	963.69 MPa	5.76	318.50	1.1339	67.82%
	4Y-PSZ	963.69 MPa	6.03	415.37	0.3038	26.20%
	3Y-TZP	963.69 MPa	8.96	837.41	0.0065	0.65%
350.000 RPM	5Y-PSZ	825.53 MPa	5.76	318.50	0.6440	47.48%
	4Y-PSZ	825.53 MPa	6.03	415.37	0.1613	14.89%
	3Y-TZP	825.53 MPa	8.96	837.41	0.0019	0.18%
400.000 RPM	5Y-PSZ	958.89 MPa	5.76	318.50	1.2223	70.54%
	4Y-PSZ	958.89 MPa	6.03	415.37	0.3186	27.28%
	3Y-TZP	958.89 MPa	8.96	837.41	0.0062	0.62%

3Y-TZP: 3 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal, 4Y-PSZ: 4 mol% Yttria-Partially Stabilized Zirconia, 5Y-PSZ: 5 mol% Yttria-Partially Stabilized Zirconia, RPM: Revolutions Per Minute, m: Weibull Modulus, Sigma0: Characteristic Strength R0: Risk of Rupture, PoF: Probability of Failure, MPa: Megapascal

Table 3. Weibull analysis for wet conditions

Speed	Material	Maximum Simulation Stress	m	Sigma0	R0 (risk)	PoF (%)
200.000 RPM	5Y-PSZ	563.94 MPa	5.76	318.50	0.0967	9.22%
	4Y-PSZ	563.94 MPa	6.03	415.37	0.0203	2.01%
	3Y-TZP	563.94 MPa	8.96	837.41	0.0001	0.01%
300.000 RPM	5Y-PSZ	526.64 MPa	5.76	318.50	0.1476	13.72%
	4Y-PSZ	526.64 MPa	6.03	415.37	0.0299	2.94%
	3Y-TZP	526.64 MPa	8.96	837.41	0.0000	0.00%
350.000 RPM	5Y-PSZ	598.83 MPa	5.76	318.50	0.1629	15.03%
	4Y-PSZ	598.83 MPa	6.03	415.37	0.0348	3.42%
	3Y-TZP	598.83 MPa	8.96	837.41	0.0001	0.01%
400.000 RPM	5Y-PSZ	624.19 MPa	5.76	318.50	0.1429	13.32%
	4Y-PSZ	624.19 MPa	6.03	415.37	0.0315	3.10%
	3Y-TZP	624.19 MPa	8.96	837.41	0.0001	0.01%

3Y-TZP: 3 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal, 4Y-PSZ: 4 mol% Yttria-Partially Stabilized Zirconia 5Y-PSZ: 5 mol% Yttria-Partially Stabilized Zirconia, RPM: Revolutions Per Minute, m: Weibull Modulus, Sigma0: Characteristic Strength R0: Risk of Rupture, PoF: Probability of Failure, MPa: Megapascal

DISCUSSION

The mechanical performance of monolithic zirconia restorations is strongly influenced by chairside adjustments performed with rotary instruments. Numerous studies have demonstrated that grinding parameters such as rotational speed (rpm), coolant application, and zirconia translucency affect surface integrity, phase stability, and ultimately the long-term strength of the material.¹²⁻¹⁶

Previous research consistently showed that grinding procedures reduce the flexural strength of zirconia compared with unaltered controls, although the extent of reduction varies.¹³⁻¹⁵ Several authors reported that high-speed handpieces combined with short grinding times tend to preserve strength better than low-speed continuous grinding, which often generates more heat and surface defects.^{13,14,16} Increased temperature during dry grinding has been associated with enhanced tetragonal to monoclinic (t→m) transformation, microcrack formation, and deterioration of mechanical properties.^{15,17} Conversely, short-term high-speed grinding with adequate coolant was found to mitigate these adverse effects.^{18,22}

In the present study, analyses revealed a complex, non-linear relationship between rotational speed (RPM), stress levels, and the probability of fracture (PoF) in zirconia. Specifically, under dry conditions, the “slower is safer” hypothesis was refuted: relatively low speeds (200000 RPM) induced high risk (77.28% PoF at 872 MPa) due to a dominant dragging/tearing mechanism caused by insufficient cutting velocity. Conversely, excessively high speeds (400000 RPM) also elevated risk (70.54% PoF at 958 MPa) due to increased centrifugal forces and impact energy.

Crucially, 350000 RPM was identified as the optimum safe point (lowest risk: 47.48% PoF at 825 MPa), where resonant vibrations were minimized and cutting efficiency was maximized. This performance is explained by the material-tool dynamic operating within a favorable stability lobe, enabling the absorption of 30%–40% of the mechanical load imposed by dry cutting. Consequently, to mitigate subsurface damage in brittle zirconia, milling strategies should target this optimum RPM band (approximately 350000 RPM).

The role of coolant application remains complex. While many studies emphasize that water cooling limits temperature rise and reduces microcrack formation,^{18, 19} others reported no significant advantage or even reduced strength under wet conditions, particularly when tungsten carbide burs were used.²⁰ This inconsistency suggests that both thermal and mechanical damage mechanisms must be considered, and the outcome likely depends on the grinding protocol.

Consistent with these reports, findings conclusively demonstrate that tribological conditions are the most critical factor governing the mechanical integrity of the material during milling. Under wet conditions, the low coefficient of friction significantly limited maximum stresses to the 520–620 MPa range, maintaining the fracture risk for even the susceptible 5Y-PSZ material within a manageable 9%–15% range. This result confirms that the coolant acts as both a lubricant and a thermal moderator, dramatically reducing the risk of critical subsurface damage during abrasion. In contrast, analyses of dry conditions showed that increased friction instantaneously elevated stresses to 820–960 MPa. This surge in stress, exacerbated by the effect of heat on material strength, drove the fracture risk in 5Y-PSZ to an unacceptable 70%–77% range. Consequently, the simulation results strongly support the engineering necessity of wet milling for low-rigidity zirconia materials like 5Y-PSZ, as dry processing constitutes a risk factor for catastrophic failure.

Material composition also determines the response to grinding. Comparative studies on zirconia with varying yttria content and translucency (3Y-TZP, 4Y-PSZ, 5Y-PSZ) demonstrated that higher-translucency materials, rich in cubic phase, generally exhibit lower fracture toughness and are less prone to t→m transformation during grinding.^{21, 23, 24} In contrast, conventional 3Y-TZP is mechanically more robust but more sensitive to surface damage. These findings underline the need to tailor adjustment protocols to the specific zirconia generation used.^{21, 23}

The present analyses confirmed this mechanical hierarchy, showing that 3Y-TZP exhibited the highest rigidity and stress levels, while 5Y-PSZ—characterized by higher translucency and lower elastic modulus—showed significantly greater total deformation,

especially under dry conditions. These findings align with existing literature, demonstrating that increasing translucency enhances optical properties at the cost of mechanical strength and stability.^{23, 24}

Overall, the literature suggests that minimizing grinding time and using high-speed handpieces with adequate coolant may help maintain the mechanical integrity of zirconia restorations.^{13-16, 21, 23-25} Nonetheless, results vary across studies due to differences in experimental setups, test methods, and material compositions, indicating the importance of further standardized investigations.

The present study contributes to this body of evidence by quantitatively demonstrating, through finite element analysis, that higher rotational speeds and coolant use collectively minimize stress accumulation and deformation in zirconia. These parameters are therefore recommended for achieving safer, more controlled chairside adjustments, particularly for highly translucent generations of zirconia.

CONCLUSIONS

Based on the outcomes of this *in vitro* investigation, wet milling emerges as a non-negotiable parameter for the safe processing of zirconia, effectively maintaining stress levels within the acceptable 520–620 MPa range. In contrast, dry milling substantially increases internal stresses (reaching up to 960 Mpa) and consequently yields an intolerable fracture probability of 77% in 5Y-PSZ. The findings further substantiate that increasing translucency is associated with diminished structural resilience; thus, the mechanically inferior 5Y-PSZ exhibits pronounced vulnerability to machining-induced damage, whereas 3Y-TZP and 4Y-PSZ remain more suitable for clinical scenarios requiring superior damage tolerance. Moreover, the commonly held assumption that reduced rotational speed enhances safety is refuted; instead, an optimized operational speed of 350000 RPM was identified as the critical threshold that mitigates resonant vibrational effects while preserving cutting efficiency. Collectively, these findings underscore the imperative of integrating wet milling, judicious material selection, and optimized RPM into clinical and laboratory protocols to ensure the mechanical longevity of zirconia restorations.

CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

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Farklı Translusesensiye Sahip Monolitik Zirkonya Seramiklerin Kırılma Direnci Üzerine Farklı Selektif Aşındırma Yöntemlerinin Etkisi: Bir SEA Çalışması

ÖZET

Amaç: Zirkonyum restorasyonların uyum ve oklüzyonunu optimize etmek için klinik ve laboratuvar aşındırma işlemleri sıklıkla gerekmektedir; ancak bu düzeltmeler yüzey defektlerine yol açabilir, faz dönüşümünü tetikleyebilir ve uzun vadeli mekanik performansı olumsuz etkileyebilir. Klinik açıdan ilgili aşındırma parametrelerinin farklı zirkonyum nesilleri üzerindeki etkisi henüz netlik kazanmamıştır. Bu çalışma, simüle edilmiş frezeleme koşulları altında 3Y-TZP, 4Y-PSZ ve 5Y-PSZ'nin tribomekanik davranışını değerlendirmeyi amaçlamaktadır.

Gereç ve Yöntemler: Alt birinci molar kronlarının (1.5 mm kalınlık) CAD modelleri oluşturuldu ve ANSYS Workbench 2022 R2'deki Açık Dinamik modülü ile sonlu elemanlar analizi kullanılarak incelendi. 1.0 mm'lik frezeleme frezesi rijit cisim olarak modellenip; 200000 ile 400000 RPM arasında değişen dönüş hızları simüle edildi. Zirkonyum malzemeler lineer izotropik elastik katılar olarak tanımlandı. Sulu ve susuz aşındırma koşulları sırasıyla 0.15 ve 0.45 sürtünme katsayılarıyla temsil edildi. Yapısal güvenilirlik Weibull istatistikleri kullanılarak değerlendirildi.

Bulgular: Susuz frezeleme, gerilme büyüklüklerini belirgin biçimde artırdı (820–960 MPa) ve 5Y-PSZ için %77'ye varan kırılma olasılıklarına neden oldu. Sulu frezeleme tüm zirkonyum türlerinde gerilimleri önemli ölçüde azalttı (520–620 MPa). 350000 RPM dönüş hızının titreşim kararsızlığını en aza indirdiği belirlendi.

Sonuç: Sulu aşındırma, yüksek translusesensili zirkonyumun mekanik bütünlüğünün korunması için kritik öneme sahiptir. Test edilen malzemeler arasında 3Y-TZP, yüksek gerilme koşullarında üstün direnç sergilemiştir.

Anahtar Kelimeler: Dental stres analizi; Dental yüksek devirli teknik; Sınırlı eleman analiz; Zirkonyum oksit