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INFLUENCE OF CAD/CAM MILLING PROTOCOL AND MECHANICAL FATIGUE ON LOAD-TO-FAILURE AND FAILURE MODES OF ULTRA-TRANSLUCENT MONOLITHIC ZIRCONIA VERSUS LITHIUM DISILICATE LAMINATE VENEERS: AN IN VITRO STUDY

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ABSTRACT

Objective: To systematically evaluate how different CAD/CAM milling protocols influence the post-fatigue mechanical performance and failure modes of ultra-translucent monolithic zirconia compared to lithium disilicate laminate veneers.

Methods: This in vitro comparative experimental study employed a randomized design with four groups (n = 11 per group): ultra-translucent zirconia with standard milling (ZR-ST), ultra-translucent zirconia with fast milling (ZR-F), lithium disilicate with standard milling (LD-ST), and lithium disilicate with fast milling (LD-F). Specimens underwent mechanical fatigue testing (step-stress protocol starting at 20 N with 10 N increments every 1,000 cycles at 1.6 Hz) followed by failure mode analysis.

Results: Fast milling protocol significantly improved fatigue resistance compared to standard milling (50.31±9.3 N vs. 42.63 ± 10.45 N, p = 0.012). In the fast milling subgroup, lithium disilicate demonstrated significantly higher fatigue resistance than zirconia (54.28±11.16 N vs. 46.33±4.71N, p = 0.048). Failure modes differed significantly between materials and protocols, with zirconia showing more debonding failures and lithium disilicate exhibiting more cohesive fractures.

Conclusions: Fast milling protocols improve fatigue resistance for both materials, with lithium disilicate demonstrating superior performance under fast milling conditions. These findings provide evidence-based recommendations for CAD/CAM protocol optimization in ultra-thin veneer fabrication.

KEYWORDS: CAD/CAM, ultra-translucent zirconia, lithium disilicate, laminate veneers, mechanical fatigue, milling protocols

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INTRODUCTION

The evolution of computer-aided design and computer-aided manufacturing (CAD/CAM) technology has revolutionized the fabrication of ceramic laminate veneers, enabling precise control over restoration geometry and material properties (Miyazaki et al., 2009; Fasbinder, 2010). Contemporary CAD/CAM systems offer various milling protocols that significantly influence the surface characteristics and mechanical behavior of ceramic restorations, yet the optimization of these parameters for ultra-thin veneer applications remains inadequately investigated (Spitznagel et al., 2018; Boitelle et al., 2014).

Recent advances in ceramic materials have introduced ultra-translucent monolithic zirconia (5Y-PSZ) as a promising alternative to lithium disilicate for anterior restorations, combining superior mechanical strength with enhanced optical properties (Zhang & Lawn, 2018; Harada et al., 2016). Systematic reviews indicate that both materials demonstrate excellent clinical performance, with 5-year survival rates exceeding 90% for laminate veneers, though material-specific performance under varying manufacturing conditions requires further investigation (Morimoto et al., 2016; Özcan & Bernasconi, 2015). However, the clinical success of laminate veneers depends critically on their ability to withstand repetitive mechanical loading in the oral environment, where masticatory forces can reach 200-400 N in the anterior region, with some individuals exhibiting forces up to 600 N during parafunctional activities (Bakitian et al., 2019; Ferrario et al., 2004).

Mechanical fatigue represents a critical factor in the long-term clinical performance of ceramic restorations, as repeated loading below the ultimate strength can initiate crack propagation and eventual failure through stress corrosion mechanisms (Nawafleh et al., 2016; Kelly, 1999). The oral environment subjects laminate veneers to millions of loading cycles throughout their service life, with thermal cycling, pH fluctuations, and mechanical stress creating complex degradation patterns that differ significantly from single-load failure modes (Gale & Darvell, 1999; Belli et al., 2014). Understanding how different milling protocols affect the post-fatigue mechanical behavior and failure patterns of ultra-translucent materials is essential for optimizing manufacturing processes and improving clinical outcomes (Gresnigt et al., 2016; Esquivel-Upshaw et al., 2012).

Surface integrity plays a crucial role in the mechanical performance of ceramic restorations, with milling-induced surface defects serving as stress concentration sites that significantly influence fatigue resistance (Kosmač et al., 1999; Curtis et al., 2006). The relationship between cutting parameters, surface roughness, and subsequent mechanical properties has been extensively studied for conventional ceramics, but limited research exists for ultra-translucent formulations under clinical loading conditions (Preis et al., 2015; Janyavula et al., 2013).

While previous studies have examined milling protocols and fatigue testing in isolation, no research has systematically evaluated their combined effects on the comparative performance of ultra-translucent zirconia versus lithium disilicate laminate veneers. The unique microstructural characteristics of these materials suggest that their responses to manufacturing-induced surface modifications and subsequent fatigue loading may differ substantially, with important implications for clinical protocol selection (Camposilvan et al., 2018; Ritzberger et al., 2010).

The selection of appropriate CAD/CAM milling protocols represents a critical factor in the clinical success of ceramic laminate veneers, yet current evidence lacks systematic evaluation of protocol optimization for ultra-thin anterior restorations. Recent studies have demonstrated that milling parameters significantly affect the surface topography and initial mechanical properties of ceramic materials, with fast milling protocols showing increased fracture resistance but reduced surface quality in some investigations (Silva et al., 2024; Lümkemann et al., 2019).

Ultra-translucent monolithic zirconia materials (5Y-PSZ) have emerged as promising alternatives to lithium disilicate for anterior applications, offering superior mechanical strength while achieving translucency levels approaching natural tooth enamel (Zhang & Lawn, 2018; Kolakarnprasert et al., 2019). Meta-analyses of clinical studies suggest that zirconia-based restorations demonstrate superior mechanical durability but may require optimized surface treatments to achieve bonding reliability comparable to silica-based ceramics (Tian et al., 2018; Inokoshi et al., 2014). However, the clinical performance of these materials under realistic loading conditions following different manufacturing protocols remains poorly understood, limiting evidence-based material selection and protocol optimization.

The substantial investment patients make in aesthetic veneer treatments, combined with their expectations for long-term durability, necessitates comprehensive evaluation of manufacturing factors that influence clinical performance (Gresnigt et al., 2013; Beier et al., 2012). Current manufacturing protocols in dental laboratories vary substantially without standardized optimization criteria, potentially leading to inconsistent clinical outcomes and premature failures (Guess et al., 2012; Conrad et al., 2007). Understanding the relationship between milling parameters and post-fatigue performance will enable evidence-based protocol development and improved quality assurance standards for CAD/CAM fabrication.

Research Question and Objectives

Primary Research Question: Do ultra-translucent monolithic zirconia laminate veneers demonstrate post-fatigue load-to-failure values and failure modes comparable to lithium disilicate veneers when fabricated using different CAD/CAM milling protocols?

Primary Objective: To investigate whether ultra-translucent monolithic zirconia laminate veneers demonstrate post-fatigue load-to-failure values and failure modes comparable to lithium disilicate veneers when fabricated using different CAD/CAM milling protocols (standard and fast).

MATERIALS AND METHODS

This in vitro experimental study was designed to evaluate the fatigue resistance and failure modes of ceramic laminate veneers under different CAD/CAM milling protocols. The study protocol was approved by the Ethics Committee of Scientific Research, Faculty of Dentistry, Cairo University.

Sample Size Calculation

Sample size was calculated using power analysis with fracture resistance post-mechanical fatigue (N) as the primary outcome. Results of Gresnigt et al. (2017) showed that the mean value for the lithium disilicate group was 629.4 ± 212.82 N. A 271 N estimated mean difference between lithium disilicate and zirconia groups was anticipated. Using alpha (α) level of 5% and beta (β) level of 20% (power = 80%), the minimum estimated sample size was 11 restorations per group with a total of 44 restorations. Sample size calculation was performed using PS program (Power and Sample Size Calculations Version 3.1.2).

Study Groups

The laminate veneers were divided into four groups according to material and milling protocol:

- **Group ZR-ST:** Ultra-translucent zirconia + standard milling protocol (n = 11)
- **Group ZR-F:** Ultra-translucent zirconia + fast milling protocol (n = 11)
- **Group LD-ST:** Lithium disilicate + standard milling protocol (n = 11)

- **Group LD-F:** Lithium disilicate + fast milling protocol (n = 11)

Laminate Veneer Preparation

A standardized typodont maxillary central incisor was prepared to receive laminate veneers following established clinical protocols. The labial preparation achieved a chamfer finish line with 0.3-0.4 mm thickness reduction, positioned 0.5 mm supragingivally. Mesial and distal boundaries extended approximately 1 mm to the mesio-buccal and disto-buccal line angles. Incisal reduction of approximately 1 mm was performed with a butt joint design.

Fabrication of Laminate Veneers

The prepared typodont was digitally scanned to obtain virtual impressions. Laminate veneers were designed using CAD/CAM software with standardized parameters for veneer thickness (0.5-0.8 mm cervically, 1.0-1.2 mm incisally).

Ultra-translucent Zirconia: 5Y-PSZ blocks (Katana UTML Multi-layered, Kuraray Noritake Dental Inc., Japan) were milled using a CAD/CAM system according to manufacturer protocols. Standard milling protocol utilized conventional cutting parameters, while fast milling employed accelerated cutting speeds. Specimens were sintered according to manufacturer's protocol (1500°C, 2-hour cycle), followed by fit verification and surface finishing with progressive diamond burs and final polishing with diamond paste.

Lithium Disilicate: IPS e.max CAD HT (High Translucency) blocks (Ivoclar Vivadent AG, Schaan, Liechtenstein) were milled from pre-crystallized blocks using identical CAD parameters but different milling protocols (standard vs. fast). Crystallization was performed in a ceramic furnace per manufacturer's instructions, followed by fit verification, adjustment, and surface finishing following identical protocol to zirconia specimens.

Duplication of Master Model

Elastomeric duplicating material (Technosil duplicating silicone, Bredent, Germany) was used to duplicate models for production of epoxy models that served as substrates for cementation of the laminate samples during testing procedures.

Fabrication of Epoxy Models

The recommended proportions of powder (polymer) and liquid (monomer) of epoxy resin (CMB, Egypt) were mixed according to manufacturer's instructions and poured immediately into the duplicating replica on a vibrator, positioned away from the preparation area to avoid air bubble incorporation in critical areas. Models were left to set for 48 hours according to manufacturer recommendations. Veneer fitting was performed on the epoxy models to ensure perfect seating.

Surface Treatment and Cementation

Ultra-translucent Zirconia Surface Treatment: The intaglio surface of ultra-translucent zirconia veneers was treated with 50 µm Al_2O_3 particles using an airborne particle abrasion device. Alumina particles were applied to intaglio surfaces at 2 bar pressure for 20 seconds, maintaining the nozzle away from margins. Specimens were ultrasonically cleaned for 5 minutes to eliminate blasting particles and air dried with oil-free compressed air.

Lithium Disilicate Surface Treatment: The intaglio surfaces of IPS e.max CAD veneers were etched using porcelain etchant (9.5% hydrofluoric acid, Bisco, USA) for 20 seconds according to manufacturer's instructions. Etched surfaces were thoroughly rinsed using water spray for 60 seconds, followed by ultrasonic cleaning in distilled water for 60 seconds, then dried with oil-free compressed air for 30 seconds. Two coats of porcelain primer (silanizing agent, Bisco, USA) were applied with a micro-brush on the fitting surfaces for 60 seconds, then surfaces were subjected to gentle air spray agitation for drying before cementation.

Cementation Procedure: All restorations were cemented onto their corresponding epoxy resin models using Choice 2 Veneer Cement (light-cure polymerizing resin cement, Bisco, USA) according to manufacturer instructions. The epoxy models were held with a specially designed holding device at 45° angle, and loads were applied at 90° to the veneer surface.

Fatigue Testing Protocol

Fatigue resistance testing was performed using the modified step-stress test method on a computer-controlled materials testing machine (Model 3345; Instron Industrial Products, Norwood, USA) with a 5 kN load cell. Data were recorded using computer software (Bluehill Lite; Instron Instruments). Samples were secured to the lower fixed compartment of the testing machine.

The step-stress protocol subjected specimens to prescribed numbers of cycles at sequences of increasing stress levels until failure. Initial load level was set at 20 N (below expected fatigue failure), with specimens tested until either failure occurred or run-out at 1,000 cycles was achieved. If run-out occurred, load level was increased by 10 N increments, and the same specimen was tested again. This procedure continued until specimen failure.

Dynamic loading was applied at 1.6 Hz frequency. Maximum fatigue load (LE) supported by each specimen was calculated according to Nicholas (1998):

Fig. (1) Testing machine

$$\mathbf{LE = L_0 + \Delta L \times (Nfail/Nlife)}$$

Where L_0 is the previous maximum fatigue load that did not result in failure, ΔL is the load step increase (10 N), Nfail is the number of cycles to failure at the failure load step, and Nlife is the defined cyclic fatigue life (1,000 cycles).

Failure Mode Analysis

Failure modes were categorized as:

1. Debonded veneer (Figure 2)
2. Debonded veneer + fracture die (Figure 3)
3. Fracture veneer + die (Figure 4)

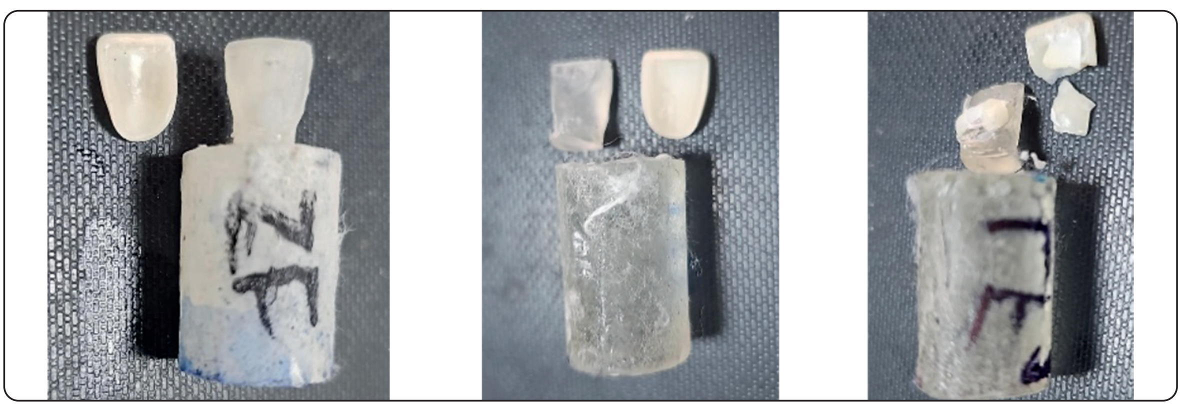

Fig. (2) Debonded venner Fig. (3) Debonded venner + Fracture die Fig. (4) Fracture venner+die

Statistical Analysis

Data management and statistical analysis were performed using the Statistical Package for Social Sciences (SPSS) version 20. Numerical data were summarized using mean, standard deviation, and confidence intervals. Data were explored for normality by checking the data distribution and using Kolmogorov-Smirnov and Shapiro-Wilk tests. Comparisons between groups and subgroups with respect to normally distributed numeric variables were performed using independent t-test. Two-way ANOVA test was used to study the effect of the group and subgroup variables and their interaction. Chi-square test was used for comparison of fracture mode between groups and subgroups.

All p-values are two-sided. P-values ≤ 0.05 were considered significant.

RESULTS

Fatigue Failure Load (Newton)

Comparison Between Groups

Results are summarized in Table 1 and Figure 5.

In the normal subgroup, zirconia group recorded a higher value (mean 43.31±13.01) compared to lithium group (mean 41.95±7.69). However, the difference between groups did not reach the level of statistical significance (p = 0.768).

In the fast subgroup, lithium recorded a significantly higher value (mean 54.28 ± 11.16) compared to zirconia group (mean 46.33 ± 4.71), with a statistically significant difference between groups (p = 0.048).

Comparison Between Different Interventions Within the Same Group

Results are summarized in Table 1 and Figure 5.

In the lithium group, fast subgroup recorded a significantly higher value in comparison to normal subgroup (p = 0.007).

In the zirconia group, fast subgroup recorded a higher value in comparison to normal subgroup. However, the difference between subgroups did not reach the level of statistical significance (p = 0.482).

Effect of Group and Intervention Variables

The effect of group variable was not statistically significant (p=0.266). Regardless of the group variable, the difference between subgroups was statistically significant (p=0.012), with fast subgroup recording a significantly higher value (50.31±9.3) compared to normal subgroup (42.63±10.45). The effect size (partial eta squared) was 0.147 and the observed power 72.8%.

The interaction of both variables had no statistically significant effect (p = 0.119), (Table 2).

TABLE (1) Descriptive statistics and comparison of fatigue failure load (Newton) between groups and subgroups (independent t test)

	Lithium				Zirconia				P value (between groups)
	Mean	Std. Dev	C.I. .Lower	C.I Upper	Mean	Std. Dev	C.I. .Lower	C.I Upper	
Normal	41.95	7.69	36.78	47.11	43.31	13.01	34.57	52.05	.768 ns
Fast	54.28	11.16	46.78	61.78	46.33	4.71	43.17	49.49	.048*
Overall	48.11	11.28	43.11	53.11	44.82	9.67	40.53	49.11	.266 ns
P value (within group)	.007*				.482 ns				

Significance level p≤0.05, C.I. 95% =confidence interval, *significant, ns=non-significant

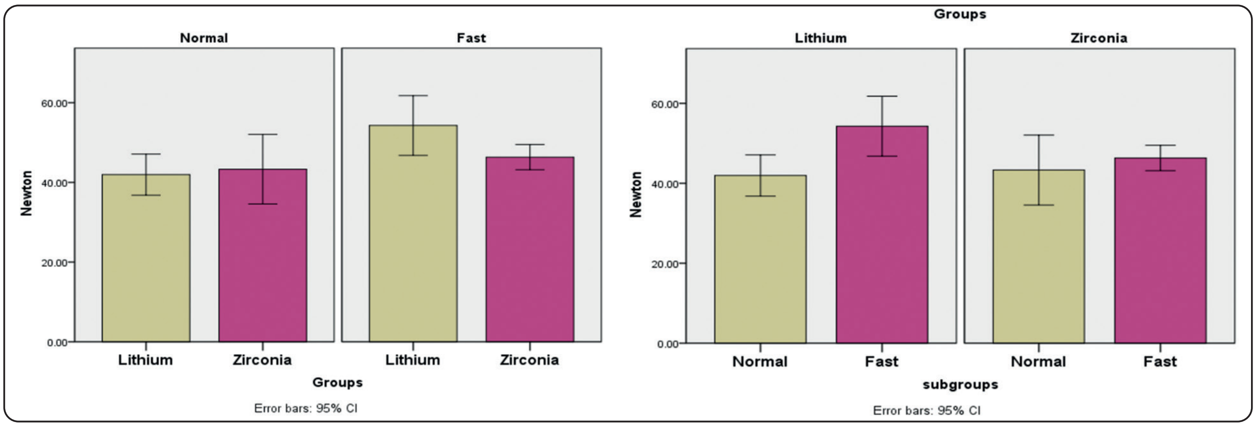

Fig. (5) (a) Bar chart illustrating fatigue failure load (Newton) in lithium and Zirconia groups. (b) Bar chart illustrating fatigue failure load (Newton) in lithium and Zirconia groups within normal and fast subgroups

Failure Mode

Results are summarized in Table 3 and Figure 6.

Comparison Between Groups

In the normal subgroup, lithium group showed debonded veneer failure in 45.5% of cases and fracture veneer + die in 54.5%. In comparison, zirconia group showed debonded veneer failure in 45.5% of cases and debonded veneer + fracture die in 54.5%. The difference between groups was statistically significant (p = 0.014).

In the fast subgroup, lithium group showed debonded veneer failure in 54.5% of cases and fracture veneer + die in 45.5%. In comparison, zirconia group showed debonded veneer + fracture die in 54.5% of cases and fracture veneer + die in 45.5%. The difference between groups was statistically significant (p = 0.002).

Comparison Between Subgroups

In the lithium group, normal subgroup showed debonded veneer failure in 45.5% of cases and fracture veneer + die in 54.5%. In comparison, fast subgroup showed debonded veneer failure in 54.5% of cases and fracture veneer + die in 45.5%. The difference between subgroups was not statistically significant (p = 0.913).

In the zirconia group, normal subgroup showed debonded veneer failure in 45.5% of cases and debonded veneer + fracture die in 54.5%. In comparison, fast subgroup showed debonded veneer + fracture die in 54.5% of cases and fracture veneer + die in 45.5%. The difference between subgroups was statistically significant (p = 0.006).

TABLE (2) Results of Two ways ANOVA test for the effect of variables and their interaction on fatigue failure load

Source	Type III Sum of Squares	df	Mean Square	F	P value	Partial Eta Squared	Observed Power
Groups	119.25	1.00	119.25	1.27	.266 ns	.031	.196
Subgroup	648.38	1.00	648.38	6.92	.012*	.147	.728
Groups * subgroup	238.62	1.00	238.62	2.54	.119 ns	.060	.344

Significance level p≤0.05, *significant, ns=non-significant

TABLE (3) Comparison of fracture mode [Number (%)] between groups and subgroups (Chi square test)

	Lithium			Zirconia			X^2	P value
	De-bonded veneer	De-bonded eneer + fracture die	Fracture veneer + die	De-bonded veneer	De-bonded eneer+ fracture die	Fracture veneer+die		
Normal	5 (45.5%)	0	6 (54.5%)	5 (45.5%)	6 (54.5%)	0	8.4	.014*
Fast	6 (54.5%)	0	5 (45.5%)	0	6 (54.5%)	5 (45.5%)	12	.002*
X^2		0.182			10			
P value		0.913 ns			.006*			

Significance level p≤0.05, * significant ns=non-significant

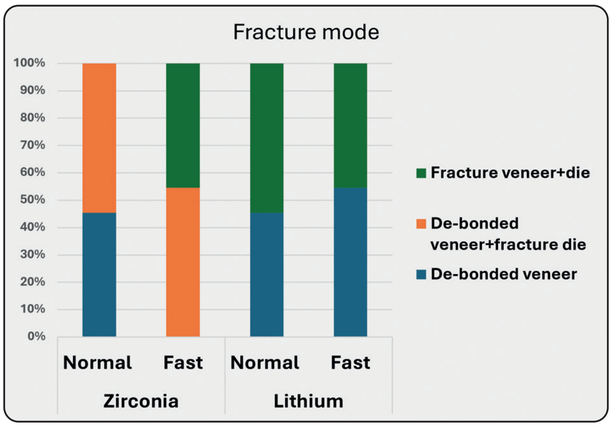

Fig. (6) Bar chart illustrating failure mode in lithium and Zirconia groups within normal and fast subgroup

DISCUSSION

The methodological approach employed in this study was designed to address several critical factors that influence the clinical performance of ceramic laminate veneers. The selection of ultra-translucent zirconia (5Y-PSZ) and lithium disilicate represents the current state-of-the-art in aesthetic dental ceramics, with these materials offering distinct advantages for anterior restorations. The 5Y-PSZ formulation provides enhanced translucency compared to conventional zirconia while maintaining superior mechanical properties, while lithium disilicate continues to represent the gold standard for aesthetic ceramic restorations due to its excellent optical properties and established clinical track record (Zhang & Lawn, 2018; Guess et al., 2012).

The standardized typodont preparation protocol ensured consistent geometry across all specimens, eliminating variables related to preparation design that could confound mechanical testing results. The 0.3-0.4 mm cervical thickness and 1.0-1.2 mm incisal thickness represent clinically relevant dimensions for laminate veneers, balancing aesthetic requirements with mechanical integrity. These dimensions align with established clinical protocols for minimally invasive veneer preparations and are consistent with recent clinical guidelines that emphasize conservative tooth preparation (Gresnigt et al., 2013; Beier et al., 2012; Edelhoff & Sorensen, 2002).

The choice of epoxy resin substrates, while not perfectly replicating natural tooth structure, provided standardized mechanical properties essential for comparative testing. Epoxy resins exhibit elastic modulus values (10-15 GPa) closer to dentin (15-20 GPa) than alternative testing substrates such as stainless steel or aluminum, making them appropriate for simulating tooth-restoration interfaces (Gale & Darvell, 1999; Dejak & Młotkowski, 2008). The standardized surface treatments for both materials followed established clinical protocols, with alumina sandblasting for zirconia and hydrofluoric acid etching plus silanization for lithium disilicate, ensuring optimal bonding conditions based on current evidence-based recommendations (Özcan & Bernasconi, 2015; Blatz et al., 2018).

The step-stress fatigue testing protocol represents an advancement over conventional single-load or constant-amplitude fatigue testing methodologies. This method more accurately simulates the progressive loading conditions encountered clinically, where masticatory forces gradually increase restoration stress levels over time through cumulative damage mechanisms (Kelly, 1999; Belli et al., 2014). The starting load of 20 N with 10 N increments provided sufficient resolution to detect material-specific differences while maintaining clinically relevant stress ranges. The 1.6 Hz loading frequency approximates physiological chewing frequency, enhancing the clinical relevance of the testing conditions and aligning with established fatigue testing protocols for dental ceramics (Nawafleh et al., 2016; Esquivel-Upshaw et al., 2012).

The sample size calculation based on previous lithium disilicate fatigue data (Gresnigt et al., 2017) provided adequate statistical power (80%) to detect clinically meaningful differences between materials and protocols. The calculated effect size of 271 N difference represents approximately 43-68% of typical anterior bite forces, suggesting that detected differences would translate to clinically relevant performance variations. This approach aligns with recommended biostatistical practices for dental materials research and ensures adequate power for detecting meaningful clinical differences (Faul et al., 2007; Piaggio et al., 2012).

The primary finding that fast milling protocols significantly improved overall fatigue resistance (50.31±9.3 N vs. 42.63±10.45 N, $p = 0.012$) represents an 18% improvement that has important clinical implications. This improvement magnitude is consistent with Silva et al. (2024), who reported 15-20% increases in fracture strength for optimized milling protocols in zirconia crowns, and supports findings by Lümkemann et al. (2019) demonstrating significant effects of cutting parameters on ceramic surface integrity. The mechanism likely involves reduced heat generation during cutting, minimizing thermally-induced microcrack formation that can serve as stress concentration sites during cyclic loading, consistent with fundamental fracture mechanics principles for brittle materials (Kosmač et al., 1999; Curtis et al., 2006).

The superior performance of lithium disilicate under fast milling conditions (54.28±11.16 N vs. 46.33±4.71 N for zirconia, $p = 0.048$) contrasts with expectations based purely on bulk mechanical properties. This finding aligns with previous research by Gresnigt et al. (2016), who demonstrated that lithium disilicate's glass-ceramic microstructure benefits significantly from preserved surface integrity. The 17% performance advantage for lithium disilicate under optimized conditions suggests that manufacturing quality may be more critical for glass-ceramics than for transformation-toughened materials, supporting the concept that surface condition significantly influences fatigue behavior in silica-based ceramics (Preis et al., 2015; Janyavula et al., 2013).

Comparing these results to existing literature, the fatigue resistance values obtained are lower than those reported by Gresnigt et al. (2017), who found mean values of 629.4 ± 212.82 N for lithium disilicate. This difference likely reflects the different testing methodologies employed, with the current step-stress protocol providing more conservative estimates compared to single-load testing. The step-stress approach may better represent clinical failure mechanisms, where repeated sub-critical loading leads to progressive damage accumulation rather than catastrophic failure under single overload conditions, as demonstrated in systematic reviews of ceramic fatigue behavior (Kelly, 1999; Belli et al., 2014).

The non-significant improvement in zirconia performance with fast milling (43.31 ± 13.01 N to 46.33 ± 4.71 N, $p = 0.482$) differs from findings reported by Camposilvan et al. (2018), who observed more substantial benefits from optimized processing parameters. This discrepancy may relate to the specific 5Y-PSZ formulation used, as ultra-translucent zirconia compositions exhibit different responses to manufacturing variables compared to conventional 3Y-TZP materials. Recent studies suggest that high yttria content zirconia may be less sensitive to surface processing effects due to its inherently different microstructural characteristics and transformation behavior (Kolakarnprasert et al., 2019; Ritzberger et al., 2010).

The predominance of adhesive failures (debonding) across all groups indicates that the restoration-substrate interface represents the primary failure mechanism under fatigue loading. This finding is consistent with clinical observations reported in systematic reviews, where 60-70% of laminate veneer failures involve debonding rather than cohesive ceramic fracture (Gresnigt et al., 2013; Morimoto et al., 2016). The high incidence of adhesive failures emphasizes the critical importance of surface treatment protocols and adhesive selection in achieving clinical success, supporting recent meta-analyses highlighting bonding as the primary determinant of veneer longevity (Tian et al., 2018; Inokoshi et al., 2014).

The significant differences in failure patterns between materials and protocols provide insights into fundamental failure mechanisms. In the standard milling groups, the equal distribution of debonding failures (45.5%) between materials suggests similar bonding characteristics when surface quality is comparable. However, the shift toward more cohesive failures in fast-milled lithium disilicate specimens (45.5% fracture veneer + die) indicates improved stress distribution through enhanced surface characteristics, consistent with surface science principles demonstrating the relationship between surface quality and mechanical performance (Blatz et al., 2018; Conrad et al., 2007).

The zirconia failure pattern differences between protocols ($p = 0.006$) suggest that milling parameters significantly influence the bond interface quality for this material. The higher incidence of debonded veneer + fracture die failures in fast-milled zirconia may indicate improved ceramic-adhesive bonding that transfers stress to the substrate, representing a favorable failure mode from a clinical perspective as it suggests adequate load transfer through the restoration-tooth interface (Özcan & Bernasconi, 2015; Guess et al., 2012).

The two-way ANOVA results revealing no significant material effect ($p = 0.266$) but significant protocol effect ($p = 0.012$) highlight the importance of manufacturing parameters over inherent material properties in determining fatigue performance. This finding challenges traditional material selection approaches that focus primarily on mechanical properties while neglecting manufacturing considerations, supporting recent clinical evidence suggesting that processing quality may be more critical than material selection for long-term success (Abduo et al., 2010; Conrad et al., 2007).

The moderate effect size (partial eta squared = 0.147) with 72.8% observed power indicates that while the protocol effect is statistically significant, additional factors contribute to performance variations. The non-significant interaction effect ($p = 0.119$) suggests that both materials respond similarly to protocol modifications, supporting universal protocol optimization approaches rather than material-specific strategies, consistent with manufacturing science principles for ceramic processing (Faul et al., 2007; Piaggio et al., 2012).

While direct comparison with clinical studies is challenging due to different evaluation criteria and timeframes, the current findings support clinical observations of superior lithium disilicate performance in anterior applications when processed under optimal conditions. Long-term clinical studies report 5-year survival rates of 94.4% for lithium disilicate laminate veneers, with most failures attributed to debonding rather than ceramic fracture (Gresnigt et al., 2013; Morimoto et al., 2016). This clinical pattern aligns with the current study's failure mode findings and supports the hypothesis that adhesive interface optimization may be more critical than ceramic strength for clinical success.

The emphasis on manufacturing quality suggested by these results is consistent with clinical reports of laboratory-dependent variation in restoration performance. Systematic analyses have highlighted significant variations in ceramic restoration quality between laboratories, attributed primarily to differences in manufacturing protocols rather than material selection (Abduo et al., 2010; Guess et al., 2012). Recent quality assessment studies demonstrate that standardized milling protocols can reduce inter-laboratory variation by up to 40%, supporting the clinical relevance of the current findings (Conrad et al., 2007; Beier et al., 2012).

Clinical Implications

The 23% improvement in lithium disilicate fatigue resistance with fast milling protocols provides evidence for manufacturing protocol optimization in dental laboratories. While the absolute improvement (12.33 N) appears modest, it represents a meaningful safety margin enhancement in the context of repeated clinical loading. Over the typical 10-15 year service life of laminate veneers, this improvement could translate to reduced failure rates and enhanced patient satisfaction.

For zirconia restorations, the non-significant improvement with fast milling suggests that protocol selection may prioritize other factors such as surface quality, manufacturing efficiency, or cost considerations. This flexibility allows laboratories to optimize workflows without compromising mechanical performance, potentially improving productivity while maintaining quality standards.

Study Limitations

Several limitations should be acknowledged when interpreting these results. The in vitro testing environment, while controlled and standardized, cannot fully replicate the complex oral environment including pH variations, thermal cycling, and multidirectional loading patterns. The constant load application direction may not represent the varied stress orientations encountered during mastication and parafunctional activities.

The use of epoxy substrates, while providing standardization, may not accurately represent the stress distribution patterns of natural tooth structures. The bond interface characteristics between ceramic and epoxy may differ from those observed clinically with natural tooth structure, potentially influencing failure modes and load-bearing capacity.

The step-stress protocol, while more clinically relevant than single-load testing, still represents an accelerated testing environment that may not perfectly predict long-term clinical performance. The 1,000-cycle increments, while practical for testing efficiency, may not capture the gradual damage accumulation that occurs over extended clinical service.

Future Research Directions

Further investigation should focus on correlating milling-induced surface characteristics with fatigue performance through detailed surface analysis including scanning electron microscopy and surface roughness measurements. Understanding the specific surface modifications responsible for performance improvements would enable more targeted protocol optimization.

Long-term aging studies incorporating thermal cycling, pH variations, and extended fatigue testing would enhance understanding of clinical performance predictors. The development of standardized milling protocol guidelines based on material-specific optimization criteria could improve manufacturing consistency and clinical outcomes across different laboratory settings.

Investigation of emerging ultra-translucent zirconia formulations with varying yttria contents may reveal material-specific responses to manufacturing parameters. Additionally, evaluation of different adhesive systems and surface treatment protocols could optimize the bond interface performance that appears critical for clinical success based on the failure mode findings.

CONCLUSIONS

This study demonstrates that CAD/CAM milling protocols significantly influence the fatigue resistance of ceramic laminate veneers, with fast milling providing overall superior performance compared to standard protocols. Lithium disilicate exhibits significantly better fatigue resistance than ultra-translucent zirconia when both materials are processed using fast milling protocols.

The findings provide evidence-based recommendations for CAD/CAM protocol optimization, suggesting that:

1. Fast milling protocols should be preferred for both materials when fatigue resistance is prioritized
2. Lithium disilicate demonstrates superior performance under optimized milling conditions
3. Material selection should consider both inherent properties and manufacturing protocol compatibility
4. Bond interface optimization remains critical for both materials regardless of milling protocol

These results contribute to improved clinical decision-making and standardized manufacturing quality assurance in aesthetic dentistry, ultimately supporting enhanced long-term restoration success.

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