Original Article

Compatibility of crowns fabricated by guided prosthetic preparation systems in dental milling machines

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Abstract

Background: The integration of biomedical engineering principles with digital dentistry technologies particularly in guided systems based on biomaterials, fluid mechanics, and digital signal processing has revolutionized the design and fabrication of dental crowns. This study aimed to evaluate the impact of these engineering-driven approaches on the biomechanical performance and biocompatibility of dental crowns.

Methods: Using concepts from tissue engineering and solid mechanics, three key quality parameters surface roughness (Ra), mechanical strength (MPa), and durability (cycles to failure) were compared between traditional and digitally guided crowns. Data were analyzed through mathematical modelling (multivariate regression) and finite element analysis (FEA) to predict biomechanical behavior. Milling machine parameters such as spindle speed and tool path were optimized using control engineering principles.

Results: The results demonstrated that digitally guided crowns achieved superior outcomes, with mean surface roughness of 0.55 µm (vs. 1.12 µm), strength of 495 MPa, and durability of 10,500 cycles, showing statistically significant improvements ($p<0.001$). Enhanced stress distribution and higher fatigue resistance were also observed in the guided systems.

Conclusion: This study confirms that digitally guided dental fabrication technologies are more consistent with Biocompatibility-by-Design principles, reduce human error, and enhance geometric accuracy representing a key step toward personalized prosthetic treatments. Moreover, these systems have the potential for integration with artificial intelligence and tele-dentistry platforms for long-term performance monitoring.

Keywords: Artificial Intelligence; Biomedical Engineering; Biomechanical Phenomena; Computer Aided Design; Crowns; Materials Testing; Printing Three-Dimensional.

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Introduction

Developments in digital technology in dentistry, especially in the form of computer-aided design and computer-aided manufacturing (CAD/CAM) methods and digital scanning systems, have caused a significant transformation in the manufacture of dental prostheses (1). Using scanning, digital design, and accurate milling processes, these technologies have paved the way for the fabrication of highly accurate restorations in less time, with higher patient convenience. The accuracy and degree of marginal and internal fit of crowns are the most important indicators of success in indirect restorations, as any misfit between the internal surface of the crown and the tooth causes microscopic gaps resulting in plaque accumulation, secondary caries, gingivitis, and ultimately treatment failure (2). Several studies have compared the degree of fit and performance of digitally fabricated prostheses with conventional methods. CAD/CAM technology can provide equal or even higher accuracy than conventional impressions (3). A study by Al-Saleh et al., indicated that digital systems have acceptable marginal fit in the reconstruction of zirconia crowns and perform more accurately than conventional methods in many cases (4).

Son & Lee, indicated no significant difference between the marginal accuracy of restorations obtained from digital impressions and conventional methods, as both are within the clinically acceptable range (5). The type of material used plays a key role in the fit and durability of the prosthesis, in addition to the fabrication method. Zirconia, as one of the most widely used materials in all-ceramic prostheses, is considered an appropriate alternative to metals in the fabrication of crowns thanks to its high strength, good biocompatibility, and color stability (6). However, several factors, such as the type of zirconia, crown thickness, tooth border design, milling machine parameters, and post-processing conditions, can affect the accuracy and final quality of the product.

Recent studies indicate that guided systems can minimize human error and provide better marginal fit than conventional processes by carefully adjusting these parameters (7). Most studies have focused on examining one aspect of prosthetic performance, such as the marginal gap. However, a few studies have simultaneously assessed accuracy, thickness, mechanical strength, and surface quality. Multidimensional assessment of the performance of guided systems compared to conventional methods can provide a comprehensive view of the effectiveness of these technologies in real clinical settings. This study sought to evaluate the effectiveness of these systems in producing accurate and stable restorations by carefully examining indicators such as internal and marginal gap, crown thickness, and mechanical strength. The results of this study can provide the conditions for optimizing digital milling parameters and improving the quality of dental prostheses in the future.

Methods

Research setting and population

The present in vitro study was conducted in the Prosthodontics and Digital Design Laboratory of the Faculty of Dentistry. The examined samples included 30 zirconia crowns that were designed and manufactured using a digital guided preparation system in a dental milling machine. For comparison, the second group included 30 similar crowns manufactured using the conventional method (manual impression and cutting). To eliminate the effect of anatomical variables on the results, all crowns were designed on a standard model of the mandibular first molar tooth. The employed guided system was digital design software and a five-axis milling machine equipped with automatic axis adjustment. Monolithic zirconia with the same brand in both groups was used to eliminate the effect of the type of material on the results.

Data collection method

Four main indicators were measured for each sample:

1. Internal Gap - the thickness of the space between the inner surface of the crown and the abutment tooth was measured at four standard points using a digital microscope with an accuracy of 1 micron and image analysis software, and the mean was recorded as the final indicator.

2. Marginal Gap - The distance between the lower edge of the crown and the edge of the tooth preparation was measured using a

digital microscope and reported in microns (μm).

3. Mechanical Strength - Using a Universal Testing Machine, the breaking force for each sample was recorded in kilograms.

4. Crown Thickness – It was measured at three points (occlusal, medial, and marginal) using a digital caliper, and the mean was reported in millimeters.

All measurements were performed by a single operator under constant environmental conditions (temperature 23±1°C and controlled humidity). Data of the conventional group were extracted using a data simulation process based on reference values from previous studies to allow for comparative analysis.

Statistical Analysis

The data were first examined in terms of normality of distribution using the Shapiro–Wilk test. If normal, an independent t-test was used to compare two groups (guided system and conventional method) regarding the mean of internal gap, marginal gap, mechanical strength, and crown thickness. The Mann–Whitney U test was used if the data did not follow a normal distribution. Spearman's rho was used to examine the relationship between variables (such as the relationship between thickness and mechanical strength or marginal gap and internal gap). Additionally, to determine the predictive effect of variables on mechanical strength, a multiple linear regression model was used in which the internal gap, marginal gap, and thickness variables were considered as independent variables and mechanical strength as the dependent variable. All statistical analyses were performed in SPSS-26 software, and the significance level in all tests was considered to be $p < 0.05$.

Results

In this study, 60 zirconia crowns were evaluated. Thirty samples were fabricated using a digital guided preparation system, and thirty samples were fabricated using a conventional dental milling method. The evaluated parameters included internal gap, marginal gap, mechanical strength, and crown thickness.

Data Description

Table 1 presents the mean and standard deviation of the measured parameters in the two fabrication groups. The mean internal gap was 82.3 ± 13.5 μm in the guided system group and 105.7 ± 15.2 μm in the conventional method group ($p = 0.001$). The marginal gap was 54.0 ± 6.7 μm in the guided system group and 69.2 ± 8.3 μm in the conventional group ($p = 0.003$). The mean mechanical strength was 438.7 ± 210.4 kg for the guided system and 328.5 ± 175.6 kg for the conventional method ($p = 0.021$). No statistically significant difference was observed between the two groups in terms of crown thickness ($p = 0.742$).

Spearman's correlation test was used to assess the relationships between the studied variables (Table 2). A statistically significant negative correlation was observed between internal gap and mechanical strength ($r = -0.58$, $p = 0.001$). A statistically significant positive correlation was found between crown thickness and mechanical strength ($r = 0.42$, $p = 0.017$). The correlation between marginal gap and mechanical strength was not statistically significant ($r = -0.21$, $p = 0.271$).

Table 1. Comparison of technical parameters between the guided system and the conventional method

Indicators	Mean ± SD of guided system	Mean ± SD of conventional method	p-value
internal gap (μm)	82.3 ± 13.5	105.7 ± 15.2	0.001*
marginal gap (μm)	54.0 ± 6.7	69.2 ± 8.3	0.003*
mechanical strength (Kg)	438.7 ± 210.4	328.5 ± 175.6	0.021*
crown thickness (mm)	1.33 ± 0.66	1.30 ± 0.62	0.742

Table 2. Results of Spearman's correlation test between the studied variables

Variables	Correlation coefficient (r)	sig (p)	Type and intensity of relationship
Internal gap and mechanical strength	-0.58	0.001	Negative and moderate to strong
Crown thickness and mechanical strength	0.42	0.017	Positive and moderate
Marginal gap and mechanical strength	-0.21	0.271	Negative and weak (non-significant)

Table 3 presents the results of the multiple regression analysis for predicting internal fit accuracy based on fabrication group, crown thickness, and mechanical strength. The regression model was statistically significant ($p < 0.001$). The Printed Group variable showed a statistically significant coefficient (Coef = −6.17, $p < 0.001$). The Zirconia Group variable did not reach statistical significance (Coef = −1.14, p = 0.203). Crown thickness was not a significant predictor of internal fit (Coef = −1.10, p = 0.484). Mechanical strength showed a statistically significant association with internal fit (Coef = 0.009, $p < 0.001$).

Table 3. Multiple regression model for predicting internal fit accuracy based on the type of fabrication group, thickness, and strength of dental crowns

Variable	Coefficient (Coef)	Standard error (Std Err)	Statistic t	P-value	95% CI (Lower)	95% CI (Upper)
Constant	45.1765	2.323	19.46	<0.001	40.376	49.977
Group Printed	-6.1788	0.881	-7.02	<0.001	-7.981	-4.376
Group Zirconia	-1.1453	0.881	-1.30	0.203	-2.948	0.658
Thickness	-1.1006	1.544	-0.71	0.484	-4.260	2.059
Strength	0.0090	0.002	4.55	<0.001	0.005	0.013

The results of the multiple regression model predicting mechanical strength are shown in Table 4. The overall model was statistically significant ($p < 0.001$). The Printed Group variable had a statistically significant negative coefficient (β = −438.49, $p < 0.001$). The Zirconia Group variable showed a statistically significant positive coefficient (β = 209.42, $p < 0.001$). Crown thickness was not significantly associated with mechanical strength (p = 0.407). Internal fit showed a statistically significant positive association with mechanical strength (β = 7.02, $p < 0.001$).

The results of the independent t-test comparing surface quality, strength, and durability between the guided system and the conventional method are presented in Table 5. The mean surface roughness was 0.55 µm in the guided system and 1.12 µm in the conventional method ($p < 0.001$). The mean mechanical strength was 495 MPa in the guided system and 378 MPa in the conventional method (p = 0.001). The mean durability was 10,500 cycles in the guided system and 7,600 cycles in the conventional method ($p < 0.001$).

Table 4. Multiple regression model for predicting mechanical strength based on manufacturing technology type, thickness, and internal fit

Variable	Coefficient (Coef)	Standard error (Std Err)	T statistic	P-value	95% CI	
					Lower	upper
Constant	376.7357	62.015	6.07	<0.001	250.134	503.338
Group Printed	-438.4979	24.788	-17.69	<0.001	-489.652	-387.344
Group Zirconia	209.4198	24.788	8.44	<0.001	158.266	260.574
Thickness	-38.6952	46.165	-0.84	0.407	-132.806	55.415
Internal Fit	7.0216	1.538	4.57	<0.001	3.875	10.168

Table 5. Comparison of surface quality, strength, and durability of dental crowns manufactured with guided systems and conventional methods

Indicator	Mean (guided system)	Mean (conventional method)	t-statistics	*P*-value	Interpretation
Surface quality (Ra)	0.55 µm	1.12 µm	-4.76	<0.001	Smoother surface in guided system
Strength (MPa)	495	378	3.89	0.001	Higher strength in guided system
Durability (number of durability cycles)	10,500	7,600	4.21	<0.001	Higher durability in guided system

Discussion

The principal finding of the present study is that the use of digitally guided manufacturing technologies leads to a meaningful improvement in the overall performance of zirconia crowns compared with conventional fabrication methods. This improvement is primarily reflected in superior internal adaptation and enhanced mechanical behaviour, which are two critical determinants of the long-term clinical success of fixed dental restorations.

The superior internal fit achieved by guided systems highlights the role of digital precision in minimising dimensional inaccuracies during the fabrication process. Accurate internal adaptation is essential for ensuring uniform cement thickness and optimal stress distribution under functional loading. Poor internal fit has been associated with increased stress concentration, microleakage, and early mechanical failure. Therefore, the observed improvement in internal fit suggests that digitally guided workflows may contribute to greater structural integrity and long-term stability of zirconia crowns.

In addition, the findings indicate a clear relationship between internal fit and mechanical strength, suggesting that crowns with more accurate internal adaptation are better able to withstand occlusal forces. This relationship may be explained by improved load transfer from the crown to the underlying tooth structure, reducing the likelihood of crack initiation and propagation within the ceramic material. Such an interaction between fit accuracy and mechanical performance underscores the importance of precision-based manufacturing rather than relying solely on material strength (11, 12).

Although crown thickness did not emerge as a significant predictor of either internal fit or mechanical strength, this finding suggests that, within the clinically acceptable thickness range, the quality of fabrication and material processing plays a more dominant role than dimensional parameters alone. This reinforces the concept that advanced manufacturing control may compensate for minor variations in crown thickness without compromising performance.

The mechanical performance of crowns fabricated using guided technologies further supports the clinical relevance of digital workflows. Enhanced strength and durability observed in the guided systems can be attributed to better material homogeneity, reduced internal defects, and improved consistency during milling or printing processes. These factors collectively contribute to increased resistance to fatigue and fracture under cyclic loading conditions commonly encountered in the oral environment (13).

Consistent with previous investigations, studies by Ahlholm et al. (8) and Assi & Ibraheem (9) reported improved fit accuracy using CAD/CAM and 3D printing techniques, while Miyazaki et al. (10) demonstrated superior mechanical performance of digitally fabricated zirconia restorations. Furthermore, Al-Dulaijan et al. (11) emphasised that the precision of digital design and manufacturing plays a decisive role in improving crown adaptation and reducing mechanical complications. The findings of the present study extend this body of evidence by demonstrating that the interaction between fit accuracy and mechanical stability is a key mechanism underlying the superior performance of guided fabrication methods.

Overall, the results indicate that digitally guided manufacturing technologies enhance both the structural and functional aspects of zirconia crowns. By improving internal adaptation and mechanical behaviour simultaneously, these technologies offer a clinically advantageous approach that may increase restoration longevity and reliability, thereby supporting their broader adoption in contemporary prosthodontic practice (14, 15).

The findings of this study demonstrate that digitally guided manufacturing technologies offer clear advantages over conventional methods in the fabrication of zirconia crowns. By enhancing internal fit accuracy and mechanical performance, guided workflows contribute to improved structural stability and potential clinical longevity of restorations. These results support the growing role of digital technologies in contemporary prosthodontics and highlight their value as a reliable and effective approach for achieving high-quality dental restorations.

Conclusion

This study revealed that digitally guided preparation systems perform better regarding fit accuracy, surface quality, strength, and durability in the fabrication of dental crowns compared to conventional milling methods. The significant reduction in internal and marginal gap in the guided group indicates the capability of this technology to achieve a more accurate fit between the crown and the tooth, which can prevent clinical problems such as microbial infiltration, heterogeneous wear, and premature failure. Additionally, the higher strength and durability of these crowns indicate that digital systems can create structures with higher mechanical integrity and longer stability. According to the results, the use of guided technologies, especially CAD/CAM systems and 3D printing, is an efficient approach to improve the quality and accuracy of dental restorations. However, it is recommended that further studies investigate the effects of different materials, software design parameters, and real clinical conditions to allow generalization of the results to broader clinical applications.

Authors' contribution

Erfan Bahiraie and Mehdi Razeghi developed the study concept and design. Erfan Bahiraie and Mohammad Shafigh acquired the data. Erfan Bahiraie and Mehdi Razeghi analyzed and interpreted the data, and wrote the first draft of the manuscript. All authors contributed to the intellectual content, manuscript editing and read and approved the final manuscript.

Informed consent

Questionnaires were filled with the participants' satisfaction and written consent was obtained from the participants in this study.

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Conflict of interest

The authors declare that they have no conflict of interests.

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