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Comparison of marginal adaptation and fracture strength of PEEK endocrown restorations fabricated using additive and subtractive methods

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Abstract

Aim: The aim of this in vitro study was to compare the marginal fit and fracture strength of endocrown restorations applied to maxillary canines, using different manufacturing methods.

Methodology: An extracted upper canine tooth was prepared for endocrown placement. Three methods were used to create the endocrowns: Fused Deposition Modeling (FDM) 3D printing with Essentium Polyetheretherketone (PEEK) filament, CAD/CAM milling with Juvara PEEK disk, and SLS 3D printing with Cr-Co metal (N=10). Additionally, 30 identical canine tooth replicas were produced using an Asiga 3D printer with a model resin, and the crown restorations were cemented with a resin luting cement. Fracture strengths were tested, and marginal fits were evaluated using Geomagic Control X software. Statistical analysis was performed, and Weibull analysis was used to assess fracture strength values.

Results: The laser-sintered endocrowns exhibited higher fracture strength (1351 N) compared to PEEK FDM (735.341 N) and milled PEEK (826.733 N) endocrowns. The highest Weibull modulus was found for milled PEEK (3.978), while the lowest was for the Cr-Co laser-sintered material (2.912). A significant difference in marginal fit was observed on the palatal surface of the PEEK FDM group compared to the other two groups ($p=0.048$). However, no significant differences were found on the mesial, distal, or buccal surfaces.

Conclusion: The findings indicate that PEEK endocrowns produced by FDM and milling offer clinically acceptable fracture strength and marginal fit, with PEEK being closer to the dentin elastic modulus. The significantly higher Weibull modulus of PEEK endocrowns produced by the FDM Printer and milling enables us to make more accurate intraoral fracture predictions.

Keywords: Endocrown, PEEK, FDM, fracture strength, milling, Weibull analysis

Introduction

The dental field continually seeks advanced materials to overcome the shortcomings of existing options. PEEK, a high-performance polymer, is recognized for its impressive strength and flexibility. It has been suggested for use in various dental applications, including temporary restorations, implant abutments, custom healing abutments, intraradicular posts, and occlusal splints. However, there is still a limited amount of clinical research backing these proposed uses (1).

PEEK is the most important member of the PEAK family of high-performance polymers. PEEK is a monochromatic, thermoplastic, semi-crystalline polymer (2). It has heat resistance and good processability owing to the combination of three functional groups, the non-reactivity of the phenylene rings and the flexibility of the ether group, as well as great resistance to chemical attack, high toughness and strength. It derives its hardness from the ketone group in it. PEEK is one of the metal-free restorations that can be used in dentistry. It is becoming increasingly important considering its superior properties in prosthetic dentistry and implantology (3). Due to its low elasticity modulus, PEEK enables the absorption of functional stresses through deformation, acting as a stress reliever and minimizing the forces transmitted to the adjacent teeth (1).

As a thermoplastic polymer, PEEK boasts outstanding thermal and mechanical properties, making it an ideal biomaterial for various prosthetic applications. Its stable structure enhances its strength, while also providing excellent heat resistance and chemical durability (4).

In dentistry, PEEK is widely used due to its exceptional characteristics, including excellent biocompatibility, non-cytotoxicity, and bioinert nature. It also offers advantageous mechanical properties, radiolucency, a bone-like Young's modulus of 3-4 GPa, minimal plaque retention, and high chemical stability (5). At the same time, it can successfully withstand the incoming forces with its sufficient fatigue strength and low yield strength. Since PEEK has a tensile strength of 80 MPa, carbon fiber-reinforced PEEK has a tensile strength of 120 MPa and dentin has a tensile strength of 104 MPa, it can be used in the substructures of restorations (6).

PEEK frameworks are lighter and more flexible than zirconia frameworks, potentially lowering the likelihood of mechanical issues. However, this option tends to be more expensive than traditional restorations (7).

The easier repairability of PEEK material compared to ceramics, its resistance to wear in the mouth and preservation of material properties during the process increase its use as a prosthesis. With its low elasticity modulus and high wear resistance, PEEK is a viable alternative to metallic alloys in removable partial dentures. Although its retention is lower than cobalt-chromium, it offers advantages such as absence of metallic taste and allergic reactions, good polishability, low plaque accumulation, and high abrasion resistance (8).

PEEK can be used as a framework material for full dentures to reduce deformation and midline fractures. However, at 1 mm thickness, its reinforcement is limited compared to stronger alternatives like fiber-reinforced composites, zirconia, and cobalt-chromium-molybdenum alloys, which offer superior strength even at 0.5 mm (9).

Root canal-treated teeth can be rehabilitated using various methods, including direct composite resin fillings, inlay and onlay restorations, full crown restorations, and post-core crown restorations (10). There is much debate and disagreement in the literature regarding the ideal restorative treatment. The initial focus is on preserving healthy tooth tissue, followed by the need for less-invasive restorative procedures that ensure the restoration's stability with the tooth through adhesive procedures. Post-core crown restoration may pose additional risks such as root canal perforation and even root fracture. To overcome these disadvantages, endocrown has emerged as an alternative restorative option for endodontically treated teeth (11).

In contrast to traditional crowns, endocrowns offer a more straightforward procedure with minimal stress, require less clinical time, are cost-effective, simple to apply, and provide superior aesthetic outcomes. One of the benefits of endocrowns is that they preserve more healthy tissue compared to other methods. When endocrowns are used, the chewing forces at the tooth/restoration interface are efficiently distributed across the entire restored tooth structure (12). When we look at the properties of PEEK, it has a modulus of elasticity of 4 GPa, which makes it as flexible as bone and allows it to be shaped as a stress breaker. This would make the use of PEEK a suitable alternative for the reconstruction of endodontically restored teeth (13).

PEEK prostheses can be produced using CAD/CAM systems from ready-made PEEK disks. Another method is to produce them by heat pressing in a vacuum press device. With this method, wax modeling is first done, wax models in a mold are heated between 630-850 degrees in a preheating oven, the melted wax is then cooled to 400 degrees. PEEK is melted and after the pressing procedure carried out in a vacuum environment, the mold is cooled to room temperature within 35 minutes while maintaining the press pressure (14). PEEK can also be processed by traditional methods such as extrusion, injection molding and compression molding (15). For materials with high melting temperatures such as PEEK, selective laser sintering (SLS) and FDM are among the production methods. FDM, which is more economical than SLS, has been increasingly tried for PEEK production in recent years (16). FDM is a low-cost, accessible method with minimal risk of material degradation (17).

While the chewing force applied in daily life varies between 222N-445 N (mean 322.5N) for a premolar tooth, the highest biting force in the presence of parafunctional habits such as teeth clenching is reported to be between 520N-800N (mean 660N) (18).

The values that indicate the variability of fracture in different groups are the Weibull modulus values. Low modulus values indicate that the measurements have high variability and that the fracture strengths have very different distributions, while high modulus values indicate that the measurements are close to each other, and the samples have very little variability.

Good marginal fit is essential for long-term dental restorations. Despite adequate marginal adaptation, there is always a microscopic gap at the restoration interface. The cement agent may dissolve in this area. To minimize this problem, the margin of the restoration should be adapted to the tooth preparation as precisely as possible. Studies indicate that a marginal gap of <120 µm is acceptable (19). The methods used to assess marginal fit are: sectioning measurement technique, micro-CT technique, three-dimensional surface scanning measurement technique, resin replica technique, silicone replica technique, direct die impression technique. Geomagic control X software is an advantageous application method as it provides non-invasive and objective, accurate data included in the classification of three-dimensional surface scanning measurement techniques (20).

This study aimed to compare the marginal fit and fracture strength of PEEK endocrown restorations fabricated using additive and subtractive manufacturing techniques. The null hypotheses tested were as follows: H_{01} – there is no significant difference in fracture strength between endocrowns produced by the two fabrication methods; and H_{02} – there is no significant difference in marginal fit between endocrowns fabricated by additive and subtractive techniques.

Materials and Methods

G*Power, version 3.1 (Heinrich-Heine Düsseldorf University, Düsseldorf, Germany) was used to calculate the sample size. Power analysis indicated that at least 5 samples per group were required to achieve 81% power with a 95% confidence interval and an effect size of 0.50. As a result, 10 samples were included in each group (n=10).

An extracted canine tooth was preferred in the study. We preferred the canine tooth because it is a tooth that we tried to keep in the mouth even if the crown damage is high because the root length is long anatomically. The tooth was placed on a plaster model and prepared for endocrown preparation. Preparation was performed by a 2 to 3 mm cuspal reduction, a marginal width of 1 to 2 mm, gutta-percha removal to a depth not exceeding 2 mm, all cervical margins were finished as supragingivally as possible, and included smooth internal transitions and a relatively flat pulp chamber. The prepared tooth was scanned with an intraoral scanner (CEREC Omnicam, Dentsply Sirona, York, PA, USA) and transferred to the inLab CAD Software (Dentsply Sirona, York, PA, USA), and the endocrown was designed. The files were created in STL format. The created STL files were directed to the relevant programs to be produced with 3 different methods.

Ten pieces were produced with Essentium PEEK (Essentium, Inc., Austin, TX, USA) filament from FDM type 3D printer with a nozzle 4200, table 1500, and speed 1200 mm/min (Printing parameters used are summarized in Table 1), ten pieces were milled with CAD/CAM using a Juvara PEEK disk (Juvora Ltd., Thornton-Cleveleys, UK), and ten pieces were produced with Cr-Co metal from SLS type 3D printer. On the other hand, 30 replicas of the prepared upper canine teeth were produced using a model resin on the Asiga 3D printer (Asiga, Alexandria, NSW, Australia). Thirty identical crown restorations were cemented to their models with Panavia F 2.0 (Kuraray Noritake Dental Inc., Okayama, Japan) resin luting cement under a 10 N static load for 10 minutes using a specially designed loading device according to the manufacturer's instructions (Fig. 1). After hardening, excess cement was removed with a scalpel, and the marginal interface was corrected with flexible disks. The created endocrowns were scanned with a plaster model scanner (inEos X5, Dentsply Sirona, York, PA, USA), and 4 points were selected from the marginal regions as buccal, lingual, mesial, and distal and directed to the Geomagic Control X software (3D Systems, Rock Hill, SC, USA) to check the marginal fit, and then the Reference Data and Measured Data were loaded. After the Initial Alignment option, the Best Fit option was clicked, and the images were matched. By clicking on the 3D Compare option, the minimum-maximum range values were set to ±0.05, and the tolerance amount was set to ±0.02. Then, by going to the Comparison Point tab, the minimum-maximum and tolerance amounts were changed again.

Figure 1. Cementation of the produced endocrown restorations under 10 N static load.

Cemented endocrown restorations were subjected to compressive loads with a 5-mm diameter steel ball placed in the center of the occlusal surface between the buccal and palatal cusps on a universal testing machine Autograph AG-X plus (Shimadzu Corp., Kyoto, Japan) with a crosshead speed of 1 mm/min until deformation occurred, and the deformation loads were recorded. The resulting data were generated in the TRAPEZIUM X software (Shimadzu Corp., Kyoto, Japan).

Statistical Analysis

SPSS software (version 22.0; IBM Corp., Armonk, NY, USA) was used for data analysis. The mean ± standard deviation values are presented; one-way ANOVA and post hoc Tukey tests were used for comparisons among more than two groups. The evaluation of the variability between the fracture strength samples was examined with Weibull analysis using the Minitab V14 software (Minitab, LLC, State College, PA, USA). The maximum likelihood method was used to estimate the Weibull parameters. The chi-square test was used to compare Shape and Scale parameters. Significance level was accepted as p<0.050.

Table 1. Printing parameters used in the study.

Printing parameters	
Nozzle Diameter (mm)	0.3
Layer height (mm)	0.1
Printing temperature (˚C)	420
Build plate temperature (˚C)	150
Print speed (mm/m)	1200

Results

In the analysis where fracture strengths were tested, it was determined that the endocrown produced with Laser Sinter showed a significant difference from the other two groups. Metal endocrowns produced with Laser Sinter (1351.441N) showed higher fracture strength than PEEK endocrowns produced with 3D printer (735.341N) and milled (826.733N). No significant difference was found between PEEK endocrowns produced with a 3D printer and milled. Evaluations of the fracture strength test are shown in Table 2.

The variability in fracture strength across different groups is assessed using the Weibull modulus. A low modulus indicates wide dispersion and high variability among the measurements, whereas a high modulus reflects consistent fracture values with minimal variability between samples (Fig. 2). PEEK Milling material has the highest Weibull modulus value of 3.978, while Laser sintered material has the lowest Weibull modulus value of 2.912 and is shown in Table 3. There is no statistically significant difference between the modulus values according to the materials (p=0.622).

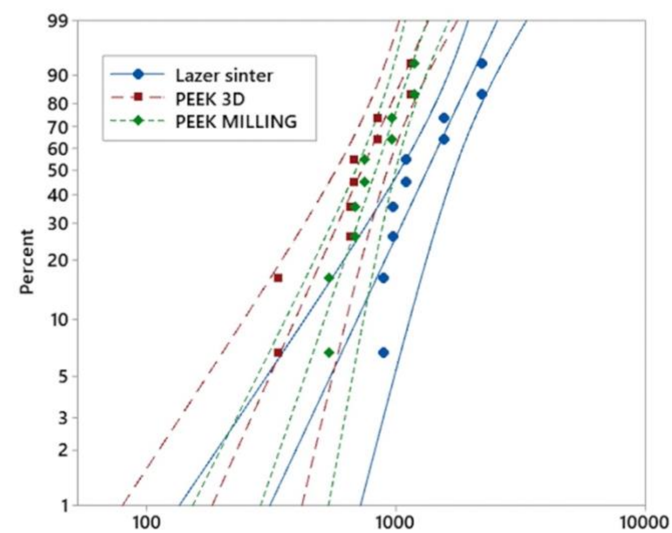

Figure 2. Probability graph of fracture strength.

Table 2. Fracture strength test evaluations (N).

	Material						
	Laser Sinter		PEEK FDM 3D		PEEK Milling		p
	Mean	SD	Mean	SD	Mean	SD	
Max Force *	1351.441[1]	521.397	735.341[2]	280.302	826.733[2]	238.940	0.002

Different superscript letters indicate statistically significant differences between groups (p<0.05).

Table 3. Weibull analysis results.

Material	Shape (m)		Scale	
	Shape (%95 CI)	SD	Scale (%95 CI)	SD
Lazer sinter	2.912 (1.83 - 4.631)	0.689	1519.78 (1211.92 - 1905.84)[a]	175.521
PEEK FDM 3D	3.064 (1.875 - 5.009)	0.768	824.401 (666.164 - 1020.22)[b]	89.643
PEEK Milling	3.978 (2.464 - 6.421)	0.972	913.603 (774.513 - 1077.67)[b]	76.987
Test statistics	0.949		17.421	
p*	0.622		<0.001	

Different superscript letters indicate statistically significant differences between groups (p<0.05).

The Scale parameter is expressed as the Scale or Spread parameter. It expresses the typical fracture strength and is related to the average fracture strength of the material. It shows what the fracture strength will be if 63.2% of the material will break or fail. High-scale values indicate that the data is spread more. Scale values vary according to the materials (p<0.001). A significant difference was obtained between the Laser Sinter group and the other materials.

On the palatal surface, the PEEK 3D group (0.184 mm) was significantly different compared to the Laser Sinter (-0.094 mm) and Milling PEEK (0.026 mm) groups, and the marginal fit values were found to be higher in the PEEK 3D group compared to the other two groups. No significant difference was found between the 3 groups on the mesial, distal, and buccal surfaces, and the marginal fit evaluations are shown in Table 4. The measurements made from the points determined in the Geomagic program to determine the marginal fit values show that the tested sample is wider in the part shown in blue and narrower in the part shown in red from the reference data, as it goes from blue to red (Fig. 3).

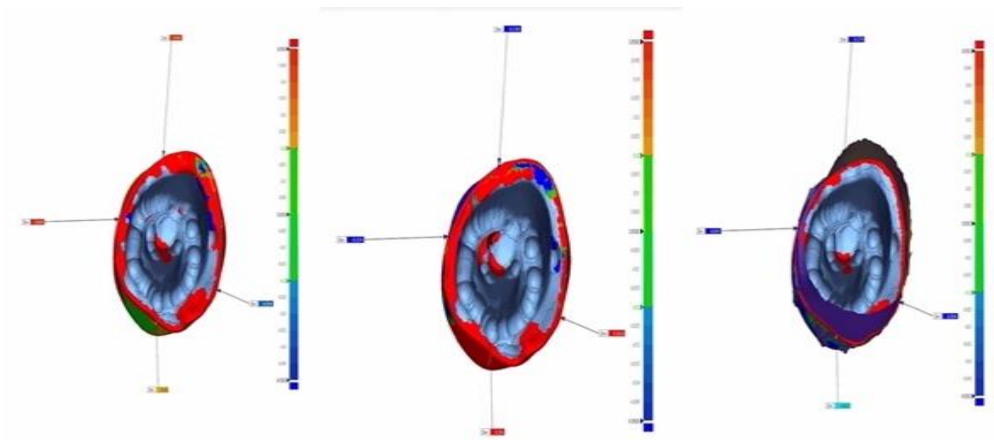

Figure 3. Geomagic control X images of PEEK endocrowns produced with 3D Printer, Laser Sinter and Milling, respectively.

Table 4. Marginal Fit Assessments (mm).

	Material						
	Laser Sinter		PEEK FDM 3D		PEEK Milling		p
	Mean	SD	Mean	SD	Mean	SD	
Mesial	-0.121	0.164	-0.218	0.417	-0.020	0.008	0.252
Distal	-0.073	0.037	0.003	0.283	0.032	0.014	0.125
Buccal	-0.089	0.058	-0.12704	0.504	0.030	0.040	0.469
Palatal*	-0.094^{1}	0.159	0.184^{2}	0.383	0.026^{1}	0.009	0.048

Different superscript letters indicate statistically significant differences between groups (p<0.05).

Discussion

The null hypotheses tested in this study are H_{01}, no difference is observed between the fracture strengths of endocrown restorations manufactured with different methods and H_{02}, no difference is observed between the marginal fits of endocrown restorations manufactured with different methods. Our first hypothesis was rejected as the fracture strength of Cr-Co material was found to be significantly higher than PEEK materials (p=0.002). Our second hypothesis was accepted as there was no difference between the marginal fits in 3 directions according to the marginal fit results examined in 4 directions.

In an in vitro study by Stawarczyk et al., it was found that three-unit fixed dental prostheses milled from pre-pressed PEEK materials using CAD-CAM technology showed lower deformation and higher fracture load (2354 N) compared to those pressed in granular form (1738N) (21). In a study conducted by Stawarczyk et al., milled three-unit PEEK frameworks demonstrated deformation of the fixed prostheses under a load of 1200 N, with connector fracture occurring at 1383 N (22). Bathala et al. and Beuer et al. They reported that the fracture resistance of CAD-CAM milled PEEK prostheses (2354 N) was much higher than lithium disilicate glass ceramic (950 N), alumina (851 N), and zirconia (981-1331 N) (21, 23, 24). In our study, metal endocrowns produced with laser sinter, 3D printer-produced and milled PEEK endocrowns were compared in terms of fracture resistance and metal endocrowns produced with laser sinter (1351.441 N) showed higher deformation resistance compared to the other two groups. No significant difference was found between PEEK endocrowns produced with a 3D printer (735.341 N) and milled (826.733 N). Although the fracture resistance of PEEK disks used in the studies was higher than our study, it was within the values for intraoral use in all cases. We stopped the device when deformation started in the test device, we did not wait for material to break completely.

Taufall et al. evaluated the fracture resistance of PEEK three-unit FDPs with various veneering techniques, including CAD-CAM, light-polymerized composites, and prefabricated veneers. Digitally fabricated veneers showed the highest fracture load, suggesting greater reliability than conventional methods (25).

In a study conducted by Jin et al., the researchers compared the bond strength of modified PEEK and titanium materials, both produced using CAD-CAM, when paired with veneer composite resin. They also compared the marginal fit and fracture resistance of implant-supported, screw-retained fixed dental prostheses (FDPs) made using CAD-CAM and veneered with composite resin. The average marginal gap was 19 ± 4 µm for the modified PEEK material and 16 ± 6 µm for the titanium material (26). In our study, in the samples examined in terms of marginal fit, it was significantly different in PEEK 3D group (0.184 mm) on the palatal surface compared to Laser Sinter (-0.094 mm) and Milling PEEK (0.026 mm) groups, and the marginal fit values were higher in PEEK 3D group compared to the other two groups. No significant difference was found among the three groups on the mesial, distal and buccal surfaces. This showed that PEEK material produced by milling and additive manufacturing methods can be used in the mouth.

Fracture resistance plays a critical role in ensuring the long-term success of implant-supported prostheses. In an in vitro experiment, Nazari et al. compared three-unit implant-supported fixed prostheses placed on two implants, made from zirconia, nickel-chromium alloy, and milled PEEK. The recorded failure loads were 2086 ± 362 N, 5591 ± 1200 N, and 1430 ± 262 N, respectively (27). In another study, Haralur et al. evaluated the fracture resistance of endodontically treated teeth (ETT) restored with different aesthetic post materials, such as fiber-reinforced composite posts (FRC), PEEK, and polymer-infiltrated ceramics (PIC). The results demonstrated that the ETT restored with a PEEK post exhibited the highest fracture load (1929.94 N), followed by the PIC post group (1810.65 N) and the FRC post group (1715.68 N) (28). The fracture strength reported for milled PEEK prostheses is higher than the physiological maximum posterior chewing force of 870 N. In our study, the PEEK deformation value is 735N-826N for the FDM-type printer and milled products, respectively. Since PEEK is a ductile material, the N value is found high in studies that observe its fracture. However, to find a clinically significant value, observing the moment of deformation and stopping the descent of the test device load arm gives the most accurate result.

Cekic-Nagas et al. evaluated the load-carrying capacity of inlay restorations obtained using CAD-CAM PEEK, PMMA, composite resin and fiber-reinforced composite. It was concluded that PEEK has the highest load-carrying capacity (29).The fact that the elastic modulus of PEEK is close to dentin, that it is a light material, that it can be produced with easily accessible methods using 3D printers and that the studies conducted show that it is very suitable for intraoral use; especially as endocrown, inlay and post will increase its use.

Prechtel et al. compared a milled PEEK material, a conventional direct resin composite material and intact teeth. They aimed to investigate the effect of chewing simulation combined with thermal cycling on the fracture load of different 3D printed Class I inlay materials. All of the milled indirect PEEK and 3D printed inlays, as well as the direct resin composite inlays, presented a fracture load higher than the expected physiological and maximum masticatory forces. ESS (Essentium PEEK) and TET (Tetric EvoCeram) direct resin composite inlays showed the lowest fracture load with a minimum of 956 N, while intact molars showed the highest values up to 2981 N. The fracture values of ESS (Essentium PEEK) material were reported to be between 769.1 and 1151, and the Weibull modulus was 4.2 (1.9-8.6). No effect was observed in chewing simulation (30). In our study, the average deformation value of ESS (Essentium PEEK) material was found to be 826.733 N and the Weibull modulus was 3.978.

In a study conducted by Al Fodeh et al., they reported that the chewing force of a premolar tooth in the mouth varies between 222-445 N (average 322.5 N), while the highest biting force in the presence of parafunctional habits such as teeth clenching is between 520-800 N (average 660 N) (18). As a result, in our study, the fracture strengths of PEEK endocrowns produced with 3D printing and milling are within the limits of intraoral use.

Limaye et al. discovered that 3D printing of PEEK produces objects with significantly lower mechanical properties (such as tensile strength, bending, and fracture toughness) compared to milled PEEK. Nevertheless, the mechanical properties of FDM PEEK remain within a range similar to that of natural cortical bone, positioning both types of PEEK as viable alternatives to other bone substitute biomaterials, including titanium (17). In our study, FDM type 3D printed PEEK (735.341N) and milled PEEK endocrowns (826.733N) showed statistically similar fracture strengths. Since the fracture strength of FDM-type 3D printed PEEK material is sufficient for the mouth, its marginal fit is acceptable, and the fracture range can be predicted with the Weibull value, smoother prosthesis types should be tried to be produced by differentiating the restoration types and nozzle degrees in FDM-produced PEEKs.

Attia et al. used Micro-CT to compare the marginal and internal fit of milled and pressed PEEK crowns. Milled crowns showed significantly superior fit (44 ±3 µm) compared to those pressed from pellets (92 ±3 µm) and granules (137 ±7 µm), highlighting the strong influence of manufacturing technique on crown adaptation (31).

In a study investigating the fit and accuracy of PEEK post-cores obtained with heat pressing techniques, additive and subtractive methods for premolar teeth, it was concluded that the additive method did not show sufficient fit and accuracy. The fit of the PEEK post-core in the marginal region with additive manufacturing was found to be within the acceptable range of 106.6 µ (32). In our study, only the distal region was observed to have an acceptable fit of 0.003 mm. Palatal-buccal-mesial regions were over 120 μ. The marginal fit values of endocrowns produced with laser sinter or milling methods on all surfaces were under 120 μ.

The limitations of this study are accepted. Since the group samples do not mimic the oral environment conditions (hot-cold, acid-base change), they cannot fully mimic the PEEK and Cr-Co materials found in the oral environment. The accuracy parameter was examined by taking 4 determining points as marginal fit, and precision values can be measured in different studies.

Conclusion

The fracture strengths of PEEK endocrowns produced by printer and milling are within the limits of intraoral use.

The fact that there was no significant difference when comparing the marginal fits showed that lighter materials, closer to the dentin elastic modulus, and more accessible production methods could be used for endocrown.

The marginal fit of endocrowns produced by subtractive manufacturing and milling is clinically acceptable in all regions, whereas the FDM-based additive method achieves acceptable fit in only one region.

The significantly higher Weibull modulus of PEEK endocrowns produced by printer and milling enables us to make more accurate intraoral fracture predictions.

Disclosures

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