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Original Article

An *in vitro* investigation of the fracture strength of root-filled - posterior teeth restored with polymer full-coverage crowns

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Abstract

Objectives: To investigate, by an *in vitro* study, the fracture strength of root-filled teeth restored with polyetheretherketone (PEEK) full-coverage crowns.

Materials and Methods: Two single-rooted maxillary second premolar Typodont teeth were prepared according to the standardized preparation guidelines for two different full-coverage crown restorations: computer-aided design/computer-aided manufacturing monolithic lithium disilicate crowns (E.max) for the control samples and machine pressed monolithic PEEK crowns for the test samples. Teeth were duplicated in a polyurethane-based resin, with properties analogous to human dentin; $n = 5$ for each category. Replicas were embedded in polyurethane-based resin material using a retaining copper ring, with a simulated 200-μ periodontal ligament. Subsequently, all samples received orthograde root canal treatment using standardized preparation and obturation techniques. Crowns were cemented with resin-modified glass ionomer cement using a standardized cementation force. All teeth were subjected to a monotonic, axial static load of 2500 N to the point of fracture.

Results: All control group samples displayed failure as a combined crown/tooth fracture. The crowns in the test group samples (PEEK) did not fracture under the experimental loads. Under the maximum loads, the crowns exhibited plastic deformation visible as an indentation created on the occlusal surface. Subsurface cohesive damage of the interface cement was noted. *T*-test showed that the resistance to fracture of the test group compared to the control group was highly significant ($P < 0.001$).

Conclusions: Within the limitations of this study, PEEK crowns help preserve the remaining tooth structure and provide more predictable protection when compared to E.max crowns. They demonstrate failure by surface deformation and subsurface cohesive damage to the interface cement layer. It is unknown if this failure mode would occur under normal masticatory loads.

Keywords: Cuspal coverage crowns, fracture strength, lithium disilicate crowns, polyetheretherketone crowns, root canal treatment

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INTRODUCTION

After endodontic treatment, the tooth structure is considered to be compromised.[1-6] Therefore, it is essential when restoring functional and esthetical demands to preserve the remaining tooth structure from fracture, to prevent microbes in the oral cavity from re-infecting the root canal system and periapical tissues, and to restore the coronal structural integrity and occlusal function.

Endodontically treated teeth (ETT) are thought to be more prone to fracture due to loss of vitality. Sedgley and Messer, however, suggest that teeth do not become more brittle after root canal treatment, based on an apparent resemblance in the biomechanical properties of ETT and their contralateral vital teeth.[7] Their work does suggest, however, that ETT may be weakened and be more susceptible to fracture as a result of the mechanical and biochemical effects of endodontic and restorative treatment. Reeh *et al.* meanwhile indicated that access cavity preparation in root canal treatment on the posterior teeth produces only a 5% decrease in tooth stiffness, irrespective of the sequence of restorative procedures.[8] In contrast, the restorative procedures themselves were the highest contributor to loss of stiffness: occlusal cavity preparation was shown to reduce tooth stiffness by 20%, and a mesio-occlusal-distal preparation reduced stiffness by 63%. In fact, it is the combined loss of tooth tissue from caries, trauma, and endodontic and restorative procedures in the marginal ridges and occlusal isthmus that weakens teeth.

Endodontic prognosis is the most significant factor dictating the durability of ETT.[9] Adequate access preparation, effective cleaning and shaping, proper canal disinfection, and high-quality filling will, together, ensure a favorable prognosis. In addition, however, it falls upon the prosthodontic procedure to determine the forces acting on a tooth, while the amount of tooth tissue remaining following preparation determines the tooth's ability to withstand these loads since this influences its susceptibility to fracture and the amount of retention available for the restoration.

The available literature suggests the success rates of endodontic treatment ranges from 70% to 95%.[10,11] Factors that affect root canal treatment outcome include root canal anatomy, preoperative pulp condition, presence and extent of bacterial contamination in the root canal space, presence and extent of peri-radicular lesions, cleaning and shaping method, and root canal filling adequacy, in addition to the quality of coronal restoration and seal.[9] Therefore, optimal planning and management of the restorative procedure for root-filled teeth is one of the pillars that determine the success of endodontic treatment. It should be taken into consideration that most teeth needing root canal treatment had their coronal seal compromised; hence, evaluation of the existing coronal seal is essential. A type of restoration could be ideal for posterior teeth but not for anteriors and vice versa.

There are many treatment modalities to restore root-filled teeth, but it follows from the discussion above that the selection of the most appropriate method depends critically on the amount of tooth tissue remaining. Cuspal coverage restorations are considered the most desirable treatment in terms of achieving a coronal seal, preserving marginal ridges integrity, providing balanced occlusal contacts, and favorable load distribution to avoid fracture of the residual tooth tissue, and this method generally ensures the longest possible lifespan for the ETT. Intracoronal restorations are only suggested in cases where both marginal ridges are intact. Martin and Bader viewed the survival of 4–5 surface amalgam fillings in comparison to crowns, finding that crowns had a higher success rate and lower catastrophic failure.[12] A systematic review in relation to root-filled teeth has shown that direct restorations have a lower 10-year survival rate than indirect restorations (63% for amalgam, composites, and cement vs. 81% for crowns).[13]

Aquilino and Caplan found that endodontically treated posterior teeth with no cuspal coverage were lost at a 6.0 times greater rate than teeth with cuspal coverage.[14] A prospective study established that survival rate of ETT restored with crowns was better than those that did not receive crown coverage.[15] The challenge is to create a mechanical system that mimics the healthy un-restored tooth while restoring ETT that withstands loads of occlusion, resists wear, and distributes stresses without prompting the remaining tooth structure to fracture.

Metal–ceramic crowns are the most world-widely used fixed prosthodontic restoration. The reason for such success is based on their ability to last long in the oral cavity with acceptable esthetical results, excellent fit, and durability.[16] However, in spite of the favorable clinical results that have been achieved with metal–ceramic crowns, they are associated with some issues that cannot be disregarded, these being: wear of the opposing teeth, porcelain fracture/chipping, vitality loss, requiring high laboratory skills to produce highly pleasing esthetics, and fracture of the remaining tooth structure, as a result of the significant amount of tooth reduction to provide sufficient space for the metal and porcelain.[17]

All-ceramic crowns, however, have far superior esthetics than metal–ceramics as they have the ability to simulate the optical properties of natural dentition. In addition, they were found to show a similar survival rate to metal–ceramics after a mean observation period of 3 years;[17] however, this was only factual for crowns that were constructed from lithium disilicate-reinforced glass ceramics or zirconium oxide ceramics, as they perform well on the posterior teeth. Nevertheless, all-ceramic restoration may not be the ideal choice to restore endodontically treated posterior teeth in cases associated with parafunction, especially the ones constructed from zirconia due to the increased risk of delamination, loss of retention, in addition to the need of a heavy preparation to provide sufficient space for the volume of ceramic that can withstand the critical flexure, which is considered to be less conservative to the residual tooth structure. In general, they are highly rigid, brittle and may fracture through crack initiation and propagation, resulting in future failure by chipping, de-bonding, or eventually fracture. In short, their hardness contributes to their ability to resist forces of abrasion but may actually cause abrasion of the opposing tooth enamel. This finding encourages the adaption of a less rigid and abrasive technique for crown reconstruction using polymers; however, if the rigidity is reduced too far, it might jeopardize marginal adaptation and structural integrity.

Polyetheretherketone (PEEK) polymer is a new material currently used in dentistry and medicine.[18-21] The material has potential use as an indirect restoration, particularly due to its encouraging biocompatibility and excellent mechanical properties.[22] It has a high melting point (about 343°C), good dimensional stability, electrical and chemical stability, good wear resistance, radiation damage resistance, compatible with X-ray imaging, and numerous processing capabilities, which makes it an attractive material for metal-free prostheses and an area of interest that might fulfill the requirements of crowns.

The main disadvantage of PEEK for dental use, however, is its solid opaque grayish color with no translucency. Veneering composites can optimize the esthetics, but there are challenges in achieving adequate bond strength between PEEK and composite due to the former's low surface energy and resistance to surface treatment.[23] It has been suggested, however, that these challenges could be avoided by the use of methyl methacrylate-based adhesives, which allow for better bonding to PEEK using self-adhesive resin cement.[24] The depth of preparation should be taken into account as well, as it is necessary to include more depth to provide enough space for the different layers, which is considered to be more aggressive. Yet, it is worth exploring this material as it has promising and suitable properties that could support the preservation of the structural integrity of ETT.

Before conducting a costly, time-consuming, clinical testing, an *in vitro* study may aid in the estimation of *in vivo* usability for a new dental material.[25] Nevertheless, owing to the complexity of the restorations geometry, no customary method is established for measuring the strength of these configurations. Furthermore, the basic goal of the chosen methodology should be to offer data that can predict clinical performance. Biomechanical tests and analyses can significantly reduce the number of clinical studies that need to be performed to characterize the full performance of particular prostheses and help identify the mechanical failures, such as chipping, crack development, bond failure, and core fracture.[26] Experimental and analytical investigations include static loading tests, dynamic loading tests, cyclic fatigue tests, and finite element analysis. Establishing a solid foundation for PEEK by testing their properties under static loading tests before performing other experimental testing seems to be beneficial, as this method is considered to be appropriate to address the research question, since it is considered to be the most common method for assessing the structural integrity.[27,28] Irrespective of the biomechanical test chosen, attempts should be directed toward simulating as closely as possible the range of conditions associated within the oral cavity.

The main aim of this study was to investigate the fracture strength of PEEK crowns and its possible use as a reconstructive indirect prosthesis for root-filled teeth.

MATERIALS AND METHODS

The manuscript of this laboratory study has been written according to the Preferred Reporting Items for Laboratory Studies in Endodontology 2021 guidelines.[29]

The experimental specimens were made out of artificial teeth prepared to standard parameters as follows: Two identical Typodont upper right second premolars (Frasaco GmbH Berhoferstrasse Tettnang, Germany) were prepared for full-coverage crowns, according to the preparation guidelines for each group, using 6° tapering burs on a custom-built parallelometer for preparing axial walls. The occlusal surface and the finish line were prepared manually using an (ISO 879K014M) diamond-coated bur to initiate preparation and a similarly shaped long tapered tungsten carbide bur for finishing in an air turbine high-speed hand-piece and red-ring low-speed hand-piece with water spray coolant.

The control group was prepared for monolithic lithium disilicate posterior crowns (IPS E.max® computer-aided design [CAD]) according to the Ivoclar/Vivadent guidelines. Occlusal reduction: clearance should be at least 1.5 mm with rounded internal line angles. Axial wall reduction: 1.5 mm with taper between 4° and 8° and no undercut or excessive axial convergence; coronal length at least 4.0 mm; two-plane reduction buccally; beveled functional cusps. Cervical margin: a clear and continuous circular shoulder with rounded inner edges or a chamfer at an angle of approximately 10°–30° with a 1.0 mm shoulder/chamfer prepared with a flat-ended tapered diamond bur for butt joint margins that is positioned above the cementoenamel junction (CEJ) level and a smooth rounded finish with no sharp line angles all over the preparation.

The test group was prepared for monolithic PEEK posterior crowns according to the processing guide for PEEK crowns issued by (Juvora™, UK). Occlusal reduction: overall clearance of 1.5 mm to 2.0 mm. Axial wall reduction: 1.0 mm to 1.5 mm. Cervical margin: accentuated chamfer finish line of at least 1.0 mm proximal reduction. In addition, for the sake of unifying samples, other preparation criteria which have been suggested in the guidelines for (IPS E.max® CAD) crown preparation were used, specifically: axial walls taper of between 4° and 8°, beveled functional cusps, smooth and rounded finish with no sharp line angles all over the preparation, and coronal length of at least 4.0 mm.

Both samples received a wax mold at the apex to increase the root length to be 21.5 mm, being the average length for an upper second premolar.[30] Teeth were then duplicated by placing them on sticky red wax positioned in the middle of a 3 cm radius plastic cylindrical ring base so as to vertically stabilize the dried and prepared Typodont premolars. Then, a proper mix of an addition silicone impression material (Dublisil® 15, Dreve Dentamid GmbH, Unna, Germany), mixed according to the manufacturer's instructions, was poured in to construct the master die mold at the center of the ring. This silicone mold was then used to duplicate the master prepared teeth to the intended sample number for each group using a dentin-like polyurethane-based resin material (AlphaDie® MF, Schütz Dental GmbH, Rosbach, Germany). Five tooth replicas were prepared for the control group and a further five for the test group. They were then allowed to set completely before being evaluated visually under ×3.5 magnification loupes so as to exclude samples with voids, deficiencies, or other irregularities that occurred during the preparation process.

Five samples of each group is not a large sample range. Ordinarily, a power calculation before commencing study should be conducted. However, as PEEK crowns were not tested previously against lithium disilicate crowns in root-filled teeth in this manner, it is not possible to conduct a power calculation based on the data from the literature. The selected approach using five samples of each group is because all variables are identical and carefully controlled, and crown testing can be done in pentaplicate (×5 times). Depending on the outcome of the data, and if both the intra-group variation (within the same group) and the inter-group variation (comparing the two groups) was not significant, an increase in the sample size can be undertaken until being able to categorically either establish a difference or categorically not establish that difference.

The samples were mounted according to their long axis to the typodent tooth apex, with the help of a dental surveyor pin, with the coronal part embedded in a wax-boarded container mounted on 0° tilted articulator table and filled with freshly mixed addition silicone impression material (Dublisil® 15, Dreve Dentamid GmbH, Unna, Germany) until 2 mm apical to the CEJ marker line. This was done for both groups to fabricate two molds of ideal teeth alignment that was used for all samples. The duplicated samples were painted with a thin layer of die separator (Kleen Lube™, KerrLab, Brea, CA, US), and then, the coronal part of the sample was inserted into the mold before placing a copper pipe ring around the mold so as to encircle the sample root evenly. The polyurethane-based resin material (AlphaDie® MF, Schütz Dental GmbH, Rosbach, Germany) was poured into the ring and left until it reached an initial setting phase; then, the sample was gently pulled and detached from the ring base using fingers, leaving a space that resembles a socket. This was then used to create simulated periodontal ligaments (PDLs) by injecting a light body silicone impression material (President Plus® Coltène, Altstätten, Switzerland) matching the natural PDLs resilience,[31] before the sample's root was directly re-inserted back into its socket and a constant 40 N vertical pressure applied for 3 min using a universal material testing machine (Lloyds® Instrument Model LRX) with a custom-modified jig, and with a silicon putty pad (Aquasil Putty®, Dentsply-Detrey, Konstanz, Germany) attached to a tensometer so as to deliver uniform pressure against the tooth occlusal surface leading to uniform PDL thickness. Ideally, a 200 μm uniform thickness of President Plus® will resemble the natural physiological tooth movement of grade zero mobility.[32] After the recommended setting time, the excess light body silicone impression material was removed using a sharp surgical blade [Figure 1].

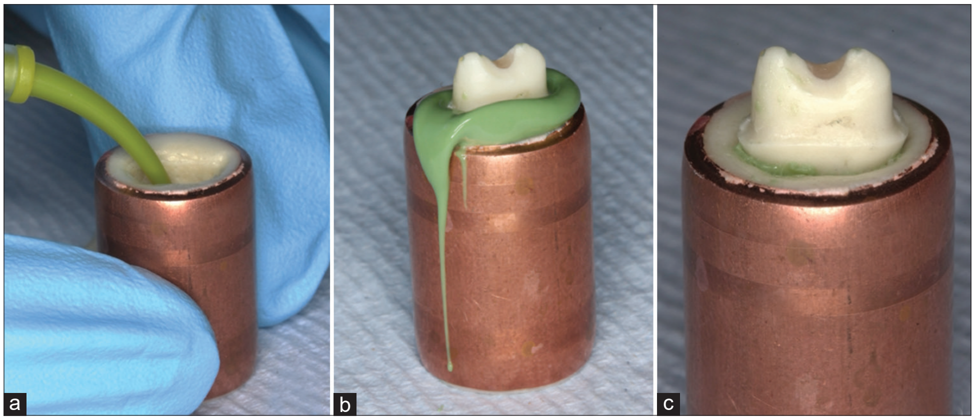

Figure 1: Creating the simulated periodontal ligaments by injecting the light body silicone impression material (a), after applying constant vertical pressure for 3 min using a universal testing machine (b), and removing the excess with sharp surgical blade (c)

The artificial teeth were then drilled to create the canal space using a universal drilling machine with steel twist drills (HSS Twist Drill) of size (0.75, 0.50, and 0.30 mm) simultaneously from the coronal one-third to the apical one-third so as to mimic the natural taper in the root canal system [Figure 2]. Following creation of the canal space, endodontic treatment was then performed for both groups by creating an access cavity preparation through the prepared crown, followed by canal cleaning and shaping using ProTaper Universal system (Dentsply Maillefer, Ballaigues, Switzerland) to a file size ProTaper F3. The irrigation used was saline so as to avoid any chemical influence that might affect the structural integrity of the artificial teeth. Cold lateral condensation technique was used to fill the canals using the gutta-percha master apical cone size F3 and zinc oxide eugenol sealer cement (Tubli-Seal™ EWT, KerrLab, Brea, CA, US). Following completion of root canal treatment, the access cavity was restored using (3M™ ESPE™ Filtek™ Supreme XTE, St Paul, MN, US) composite restoration with the total-etch technique using 3M™ ESPE™ Scotch-bond™ Universal adhesive.

The prepared Typodont teeth were digitally scanned (IPS E.max® CAD) to produce a design covering full anatomical features for both full-coverage crowns according to the crown fabrication guidelines of each group. A wax-printed crown from the digital model of the prepared die was milled using CAD/computer-aided manufacturing (CAM) fabrication technique, following the manufacturer's guidelines, to construct five lithium disilicate crowns (the control group). The digitally designed monolithic PEEK crowns were machined from an industrially pressed disc to produce a further five crowns (the test group). The teeth samples and crowns were then etched with 37% phosphoric acid for 20 s, rinsed with water, and then air-dried to remove any biofilm and grease residue from the surface, and the crowns were then loaded with the resin cement luting material (RelyX Uniceme®, 3M, ESPE, St, Paul, MN, US) before being fitted onto the prepared teeth.

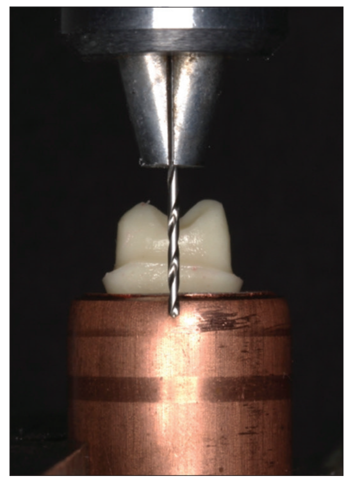

Figure 2: Twist drills of sizes (0.75, 0.50, and 0.30 mm) were used simultaneously from coronal, middle, to apical one-third to create canal with continuous taper

The sample was placed in the same universal materials testing machine (Lloyds® Instrument Model LRX) for cementation, and a customized jig holding a silicone putty impression material with an imprint of the occlusal surface of the crown (Aquasil Putty®, Dentsply-Detrey, Konstanz, Germany) for 3 min under a load of 40 N to press and hold the crown in position allowing for even constant pressure [Figure 3]. All samples were lightly polymerized at the end of the third min for 20 s by using Optilux 501 quartz-tungsten-halogen light (KerrLab, Brea, CA, US) for optimal setting, with any excess being removed using a sharp scalar, then left undisturbed for 1 h, followed by storing in distilled deionized water for 24 h before testing.

The monotonic static test is designed to evaluate the integrity of a structure and record any alterations in the material or the final restorative design. To measure

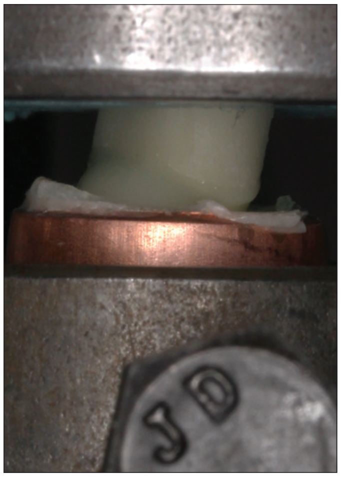

Figure 3: Crown cementation using universal testing machine with the customized jig silicone putty pad to allow for even constant pressure

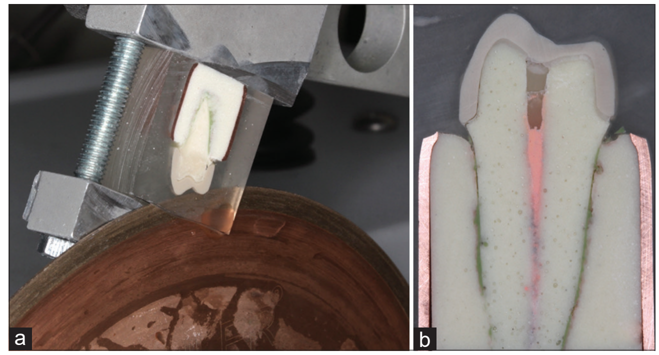

Figure 4: Cold cured acrylic blocks sectioned with diamond discs attached to a cutting machine (a), the sliced samples were polished and smoothed with diamond grinding discs for microscopic examination (b)

the fracture strength of the restoration in a static mode, a static load of 2500 N was applied through a universal material testing machine, and the maximum stress that was generated in the structure when fracture occurred was noted as that structure's fracture strength. The specimens were positioned and fixed firmly in a mounting device so that the longitudinal axis was perpendicular to the load direction; the teeth were then loaded from the occlusal surface in a fixed point at the center of the groove mesio-distal and bucco-palatal for all specimens.

The universal material testing machine with a 4.25 mm diameter steel ball plunger was used to load the specimens with a static compressive axial load at a crosshead speed of 0.5 mm/s. The specimens were loaded with a rubber dam sheet placed between the steel ball plunger and the crown to act as a stress breaker until catastrophic failure occurred demonstrated by fracture, and the ultimate failure load was recorded. In addition, the mode of failure was recorded as root fracture, crown fracture, and prosthesis fracture. The initial failure load was considered as occurring when cracks appeared in the crown or marginal de-bonding. This was applied for both control and test group samples.

Finally, the test group sample was embedded in a cold cured acrylic and sectioned with diamond discs attached to a cutting machine (IsoMet® 1000 Precision Saw, Buehler); the surface was then polished and smoothed with diamond grinding discs attached to a Metaserv®, Grinder-Polisher, Buehler [Figure 4], so as to allow any deformation to be examined under a light microscope (SteREO®, Discovery V8, Zeiss) at 8:1 magnification. After all the data were compiled, it was analyzed with a statistical software program (SPSS (IBM, USA)) by using the Student's *t*-test to compare the means of both groups to determine the statistically significant difference. One investigator will be conducting the study in a university setting.

RESULTS

During mechanical loading of the control group, all samples displayed failure as crown/tooth fracture as a result of the load applied. The load which crown fractured was recorded as maximum load. In the test group, however, the maximum load that could be applied was reached without resulting in any form of fracture to the crown or tooth structure. The crown was noticed to have an indentation created on the occlusal surface, as the steel ball plunger was marked on the central groove where it was in contact with the crown structure during testing [Figure 5].

Table 1 lists the maximum load that both control and test groups sustained before catastrophic failure manifested by fracture occurred in the control group and when the surface deformation appeared in test group. Based on the data in Table 1, an *f*-test was performed to test for homoscedasticity. Since the variance of the means in the two groups was shown to be not equal ($F > F_{critical}$; $15.00 > 6.39$), a two-sample *t*-test assuming unequal variances was performed. The greater maximum load borne by the test group compared to the control group was highly significant ($P < 0.001$) as shown in table 2.

The light microscopic examination for the test group where the steel ball plunger was loaded revealed a subsurface damage of the cement layer with fracture of the cemental interface at the site of compression, in addition to where it was in contact with the composite intracoronal restoration; however, an intact cemental aspect buccally and palatally to the fractured cemental layer was noted. Furthermore, the composite surface was found to be intact with no sign of defect. It also showed signs of compression to the crown with reduced thickness when compared to other

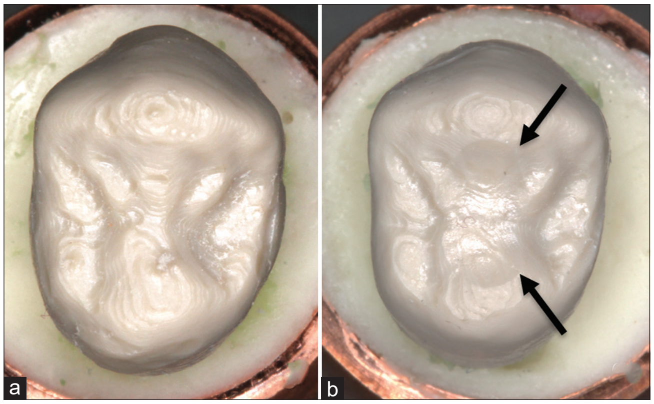

Figure 5: Crown before mechanical loading with intact occlusal surface (a), crown after loading with evidence of indentation (arrow) centralized on the occlusal surface reflecting the shape of the ball plunger (b)

Table 1: Monotonic static test to determine the maximal load when fracture occurs of the test group (polyetheretherketone) compared to the control group (E.max)

Sample number	Maximum load (newtons)
Control group (E.max)	
1	650.34
2	647.67
3	868.08
4	872.16
5	849.28
Test group (PEEK)	
1	2246.30
2	2198.50
3	2232.00
4	2263.20
5	2277.20

PEEK: Polyetheretherketone

sites of the crown that were not in contact with the steel ball head [Figure 6].

DISCUSSION

This is a developed investigation to determine the fracture strength of PEEK crowns when used to restore ETT. The main objectives are (i) creating an appropriate sample, (ii) testing the physical properties by means of compressive loading, (iii) analyzing data obtained, and (iv) examining mode of failure.

Although the methodology chosen in this study may not resemble the functional chewing relationship in a patient's oral environment and reproduce what would occur clinically, it does result in a more controllable environment to allow for a more specific evaluation of the performance of PEEK crowns.

We have been limited to the use of materials by fabrication technologies: casting, centering, and pressing. Recently, evolving technology has been introduced in the last two decades, machining by using CAD/CAM, which has become a great option for the fabrication of indirect restorations. Researches to develop new materials suitable for CAD/CAM applications are recently the fastest developing field in dental materials. Two types of materials could be used in the production of CAD/CAM restorations: polymers and glass–ceramics/ceramics, which have been used in this study. Some polymers are currently being used for fabrication of temporary crowns such as chair side Protemp™. Nevertheless, they have very low filler load, and they are poorly optimized and polymerized.[33] Therefore, their structural properties are very limited, and that is the reason for their use as temporary crowns. However, this study is considering the performance of a completely different range of polymer materials that have much higher filler load and polymerization. Polymers used in definitive dental prostheses are resin composites and PEEK, which is a new material produced by manufacturers such as Juvora® and Invibio®. It is a high temperature, semi-crystalline, high purity, thermo-plastic homopolymer comprising repeating monomers of two ether groups and a ketone group and belongs to the larger family group of polyaryletherketone.

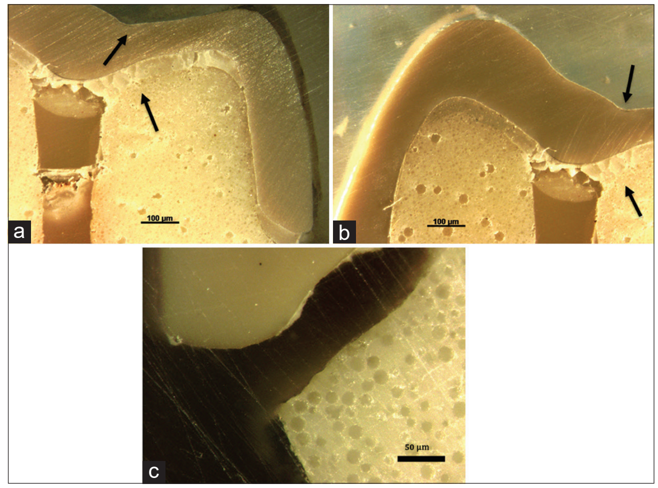

Figure 6: A postexperimental cross-sectional light microscopic examination showing fracture in cemental interface at the site of compression and compressed crown where the steel ball plunger was applied (arrows). Palatal cusp (a), buccal cusp (b). Intact cemental layer on the cervical margin between the Polyetheretherketone crown and the tooth structure after the test was completed (c)

According to a study by Brosh *et al.*,[31] the light body silicone impression material proved as the most resemblance to PDL imitating material due to its matched resilience to natural PDL. The created socket was injected with the material, and the tooth was immediately inserted into the socket. In this experiment, a space of 200 μm thickness of the light body impression material was created to allow for 50 μm movement to simulate

Table 2: Two-sample *t*-test assuming unequal variances between the test group (polyetheretherketone) and the control group (E.max)

	Control group (E.max)	Test group (PEEK)
Mean	777.51	2243.44
Variance	13835.78	922.21
t-statistic	−26.98	
t-critical two-tailed	2.57	
P	0.000001	

PEEK: Polyetheretherketone

normal physiological tooth movement of grade zero tooth mobility.[31,32]

The ideal tooth sample to address the research question, based on similar studies and on those studies that consider how the evidence from tests done on particular teeth can be extrapolated to wider conclusions, is upper second premolars.[8,34,35] The natural teeth anatomy has many variants that differed from one tooth to another: crown and root morphology, root length, root diameter and taper, root curvature, and root canal morphology. To standardize the selected tooth sample chosen in this study as much possible and to control the many variables, customized artificial teeth made from dentin-like polyurethane-based resin material AlphaDie® was produced. The artificial teeth then were drilled to create the canal space in a tapered outline to resemble the natural root canal outline within the artificial tooth. The polymer material AlphaDie® was chosen as a substitute for dentin as it has an elastic modulus closely matched to that of dentin,[36] similar to bone,[37] and has the ability to bond to the composite luting cement. It is widely used in the literature as dentin-like material.[38,39] However, it should be noted that AlphaDie® has a different structural design than dentin. Dentin is anisotropic by virtue of tubular form, while AlphaDie® is isotropic by virtue that it is a composite with evenly dispersed particles, which may lead to different mechanical behavior under loading conditions.

In this investigation, the focus was primarily on samples that have been root canal treated. It is worth noting that endodontic treatment, in particular, with fairly remaining tooth structure, does not cause teeth to become more prone to fracture,[7,8] as in fact, it is the combined loss of tooth structure and marginal ridges from the restorative procedures, along with the endodontic treatment. The evidence suggests that the survival rate of ETT restored with crowns was better than those that did not receive crown coverage.[14,15]

The data were not very consistent within E.max group (intragroup variation). There is a significant variation of nearly 200 N from the lowest fracture load to the highest; however, because the difference between groups (intergroup variation) is huge (about 1500 N), this outweighs the large (intragroup variation) mentioned above. Hence, given the huge (intergroup variation), it is reasonable to accept the data from this investigation based on ×5 samples for each group.

E.max crowns are very brittle; therefore, the fracture mode for E.max samples (control group) after being subjected to the fracture strength test was reported to be, according to Burke's classification, severe fracture of the crown and or tooth[40] as all samples were severely crushed. However, PEEK crowns are ductile and deformable; the highest value for the maximum load that was recorded for PEEK samples (test group) was (2277.20 N). The statistical analysis of the results showed that there was a statistically significant difference between the two groups with regards to maximum loads that the material can withstand before fracture. Nevertheless, the damage from subjecting PEEK crowns to occlusal compressive loading resulted in subsurface damage to the cohesive layer, and a surface plastic deformation on the occlusal surface where the steel ball head was in contact with the crown, as a result of being subjected to greater fracture load, this could be misleading as they do not fracture, in fact, they were deformed.

A light microscopic examination confirmed no signs of cracks or fractures in PEEK crowns, only showing evidence of subsurface fracture of the cemental layer at the internal cemental interface. No evidence of seal being affected, as the crown margins were intact. In addition, no damage was found on the artificial tooth structure. This suggests that restoring an ETT with PEEK crowns may help in preventing the residual tooth structure from fracture and help preserve the remaining tooth tissue.

Endodontic treatment with adequate restoration is a practical and economical method to preserve function.[41] The findings of this investigation helped answer the research question. It suggests that PEEK crowns help in better protection of the tooth tissue and preserve its structural integrity after receiving endodontic treatment. However, despite the limitation that included a small sample size, the effect of the veneering porcelain to PEEK crowns was not tested. Furthermore, tests to identify microleakage at the crown–tooth interface after such loading would help reveal whether bonding was affected. Further investigations testing the cyclic loading on PEEK crowns may further our understanding of the performance of this material in a more relevant clinical situation before *in vivo* investigations.

CONCLUSIONS

Within the limitation of this study, it showed the following:

1. PEEK crowns fail by surface deformation; this damage is not a catastrophically visual failure
2. The damage from subjecting PEEK crowns to occlusal compressive loading resulted in subsurface damage to the cohesive layer and an indentation on the occlusal surface as a result of being subjected to greater fracture load; this could be misleading as they do not fracture; in fact, they were deformed
3. PEEK crowns help in preserving the remaining tooth structure and provide more predictable protection from fracture to the ETT when compared to E.max crowns.

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Conflicts of interest

There are no conflicts of interest.

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