Original Article / Özgün Araştırma

Comparison of the Load-bearing Capacities of Monolithic PEEK, Zirconia and Hybrid Ceramic Molar Crowns

Monolitik PEEK, Zirkonyum ve Hibrit Seramik Molar Kronların Basma Dayanım Kapasitelerinin Karşılaştırılması

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Abstract

Objective: Although polyether ether ketone (PEEK) shows high biocompatibility in prosthetic dentistry, there is inadequate information about its clinical applications and limits. The purpose of this study was to compare the load-bearing capacities of PEEK, hybrid ceramic and zirconia crowns, which were fabricated using computer-aided design and computer-aided manufacturing (CAD/CAM).

Materials and Methods: Three groups (n=10) of high-resistance PEEK polymer, hybrid ceramic and zirconia were fabricated using CAD/CAM. A universal test machine was used to assume the fracture resistance of all specimens. The specimens were loaded until final fracture occurred and load at fracture was recorded. Fracture resistance data were statistically analyzed by Tukey honest significant difference multiple comparison test.

Results: There was no significant statistical difference between PEEK group (2214±236 N) and hybrid ceramic group (2325±264 N) in relation to the load-bearing capacities (p>0.05), while zirconia group (3292±192 N) showed the highest values for fracture load.

Conclusion: All three crown materials were successful against physiological occlusal forces. Regarding the limitations of this *in vitro* study, PEEK could be an alternative crown material for fixed dental prostheses.

Keywords
PEEK, hybrid ceramic, zirconia, crown

Anahtar Kelimeler
PEEK, hibrit seramik, zirkonyum, kron

Öz

Amaç: Polieter eter ketonun (PEEK) protetik diş hekimliğinde göstermiş olduğu yüksek biyouyumluluğuna karşın, klinik uygulamaları ve sınırları hakkında yeterli bilgi bulunmamaktadır. Bu çalışmanın amacı, bilgisayar destekli tasarım ve bilgisayar destekli üretim (CAD/CAM) kullanılarak üretilen PEEK, hibrit seramik ve zirkonyum kronlarının basma dayanım kapasitelerini karşılaştırmaktır.

Gereç ve Yöntemler: Yüksek dirençli PEEK polimer, hibrit seramik ve zirkonyum olmak üzere üç grup (n=10) CAD/CAM kullanılarak üretildi. Tüm örneklerin kırılma direncinin değerlendirilmesi için üniversal test makinesi kullanıldı. Örneklere kırılma meydana gelene kadar yükleme yapıldı ve kırılma anındaki yük değerleri kaydedildi. Kırılma direnci verileri Tukey-honest significant difference çoklu karşılaştırma testi ile istatistiksel olarak analiz edildi.

Bulgular: Basma dayanım kapasitelerine göre PEEK grubu (2214±236 N) ile hibrit seramik grup (2325±264 N) arasında istatistiksel olarak anlamlı fark gözlenmezken (p>0,05), zirkonyum grubu (3292±192 N) kırılma dayanımında en yüksek değerleri gösterdi.

Sonuç: Her üç kron materyali de fizyolojik okluzal kuvvete karşı başarılıydı. Bu *in vitro* çalışmaların sınırları doğrultusunda, PEEK materyali sabit protezler için alternatif bir kron materyali olabilir.

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Introduction

The main purpose of prosthetic dentistry is to use artificial materials to rehabilitate deficiencies in the teeth and oral tissues (1). For many years, metal-alloy crowns have been considered the gold standard in prosthetic dentistry. However, metal alloys have some limitations. For example, the aesthetics of these materials are limited by the metal framework and by the layer of opaque porcelain needed to mask the underlying grayish metal shade (2).

All-ceramic restorations are used as a standard in the aesthetic dentistry field due to their high aesthetic appeal, biocompatibility, and excellent mechanical properties, but they were later abandoned due to their low fracture resistance (3-5). The other framework structures, such as zirconia-based restorations, are the most commonly used due to their high strength, which reaches about 2000 MPa in fixed dental prostheses (FDPs) (6). When stabilized with Y_2O_3, zirconia offers the best properties for dental applications. However, due to the nature of metastability, zirconia-based restorations are susceptible to undesirable phase transformation at room temperature, which is known as “low temperature degradation” (7,8). This process may lead to yttrium loss, distort the stability of the tetragonal phase of zirconia-based restorations, and lead to uncontrolled tetragonal-monoclinic transformation (9). This creates surface roughness and microcracks, thus making water penetration possible. This ultimately leads to more phase transformation and consequently the mechanical loss of strength (7-10).

Any material used in prosthetic dentistry should produce satisfactory biocompatibility, aesthetic results, and mechanical properties for occlusal bites (11,12). In recent years, hybrid ceramics have been used in prosthetic dentistry due to their high biocompatibility (13). These materials, which feature the positive characteristics of both composites and ceramics, are produced to reduce abrasion from the opposite arch. This network structure of hybrid ceramics is formed by an interpenetration of ceramic and composite polymer networks; this is called a hybrid double network, and it mimics the interlocking of prism bands in natural teeth (14). The double-phase network structure of hybrid ceramics increases their fracture resistance and ensures both successful edge stability and an excellent marginal fit with oral tissues (15). The currently available member of this new hybrid ceramic group is GC Cerasmart (Cerasmart; GC America Inc, Alsip, IL, USA), which is a 71 wt% filled nanocomposite produced via computer-aided design and computer-aided manufacturing (CAD/CAM). The disadvantages of this material are that its resistance to flexibility is low and it is not as aesthetically pleasing as full ceramics are (15).

To overcome these existing problems, a new generation of composites has been proposed for prosthetic dentistry: elevated high-resistance polymers called polyether ether ketone (PEEK) (16). These highly resistant and high-performance thermoplastic polymers were first produced for industrial purposes in the 1980s and are members of the polyaryletherketone (PAEK) family, which comprises aromatic molecular chains of ether and ketone (16). The chemical structure of PEEK is similar to that of other polymers in the PAEK family. PEEK has high temperature resistance (up to 300 °C), high resistance to chemical abrasion, minimal radiation permeability, and the ability to be modified with various materials (such as carbon fibers and glass). Additionally, it can be used as an alternative to metal alloys (16-18). Due to its high biocompatibility, biostability, and radiosensitivity, along with its other mechanical properties, PEEK is an excellent alternative material for orthopedic and spinal implants (19). By the late 1990s, PEEK had emerged as the leading high-performance thermoplastic candidate for replacing metal implant components, especially in orthopedic and trauma applications (16). Today, PEEK is used in dentistry for applications such as dental implants, temporary implant abutments, removable prostheses, fixed partial dentures, implant healing caps, and implant-supported hybrid prostheses (20-22). Research has suggested that PEEK can be used to make crowns in prosthetic dentistry because the tensile strength of PEEK (80 MPa) is similar to those of dentin (104 MPa) and enamel (47.5 MPa). Thus, PEEK may have an advantage over alloy and ceramic restorations (17,18,23).

Although PEEK is a more aesthetic material than metal alloys are, it is not as transparent as hybrid ceramics are; another major disadvantage of PEEK is its low bonding strength with resin cement materials due to its low surface energy (20,24). It is difficult to establish strong and resistant adhesion between PEEK and composite resin materials owing to PEEK's low surface energy and its strength to surface modification via chemical treatments (25).

In recent years, many studies have been carried out to improve PEEK's adhesive properties using conventional sanding, acid etching, and the plasma and laser roughening methods (20,25,26).

The aim of this *in vitro* study was to compare the load-bearing capacities of monolithic crowns made of zirconia, hybrid ceramics, and PEEK. The tested null hypothesis was twofold (1). The PEEK crowns would not demonstrate higher load-bearing capacities than the zirconia crowns did (2). There would be no significant difference between the hybrid ceramic and PEEK materials in terms of fracture resistance.

Materials and Methods

Crown Preparation

For the current study, a zirconia base model (Zirconia Pre Shaded Blank; Shenzhen Upcera Co, Shenzhen, Yuè, China) with a prepared primary maxillary right first molar was used as the basic cast. The anchor teeth presented an occlusal reduction of 2.0 mm, an axial reduction of 1.5 mm, and a chamfer with a convergence angle of 6 °C (Figure 1A). Specimens were fabricated using CAD/CAM and were divided into three groups featuring 10 specimens per group.

The materials used in the study included zirconia (Zirconia Pre Shaded Blank; Shenzhen Upcera Co, Shenzhen, Yuè, China), PEEK (PEEK Optima LT1, Invivo Biomaterial Solutions, Inc., Lancashire, England), and a hybrid ceramic (Cerasmart; GC America Inc, Alsip, IL, USA).

The digital impression technique is preferred for the production of crowns. The zirconia model was scanned using a CEREC 3 intraoral scanner (Cerec Omnicam; Sirona Dental Systems Inc. NY, USA). According to the manufacturer, no powder system needs to be applied to the zirconia model before scanning. The monolithic crown was designed on the computer to have thicknesses of 1.5 mm in the axial area and 2 mm in the occlusal area. The same CAD file was used for all crowns. The cement space was set at 30 µm. The complete CAM process for the 30 crowns was conducted using a three-axis milling machine (Yena D15; Turkuaz Inc, İzmir, Turkey). Zirconia frameworks were sintered at a temperature of 1500 °C to full density in a sintering furnace (Lava Furnace 200; 3M ESPE, St. Paul, MN, USA). However, for the PEEK and hybrid ceramic crowns, only the surface-polishing process was applied, not the sintering process (Figure 1B). The same parameters were loaded into the computer software for all specimens during the production process. Thus, the crowns made of all three materials had the same standards.

Load-Bearing Capacity

A universal testing device (Universal 3345 Testing Systems, Instrons, Inc., Norwood, MA, USA) was used to determine each crown's load-bearing capacity. The load was applied in the central fossa of the crown using a steel ball (diameter 5 mm) with a cross-head speed of 0.5 mm/minute. The specimens were loaded until final fracture occurred, and the load at fracture (N) was recorded (Figure 2).

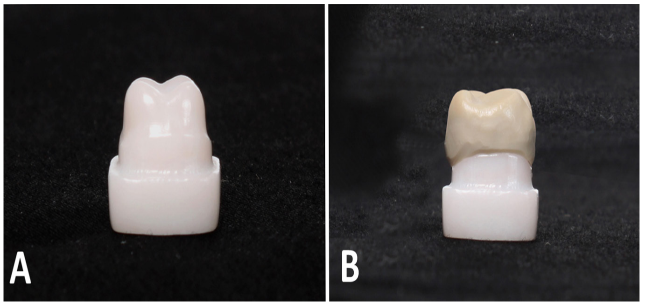

Figure 1. A) Photograph of a zirconia model, B) PEEK crown on zirconia abutments before fracture load measurement

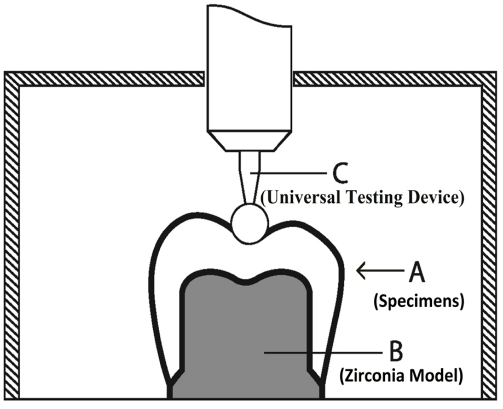

Figure 2. Schematic view of Load-bearing capacity tests. A) All specimens B) were fixed using the zirconia model and C) loaded on the central fossa of the frameworks along to the long axis using stainless steel rod with 5-mm diameter ball end

Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum, median, maximum, and 95% confidence interval) were computed. Significant differences between the groups were tested with one-way ANOVA ($F=64.72$; $p<0.001$). For the data of all of the groups, Levene's test was used to verify the homogeneity of variances The Kolmogorov-Smirnov test was applied to the test data in a normal distribution within the groups. Tukey honest significant difference (HSD) tests were used to determine statistical significance. All of the statistical analyses were performed using R version 3.2.3 Copyright © 2015 The R Foundation for Statistical Computing free software. The level of significance was set at 5% ($p<0.05$).

Results

The load-bearing average, maximum and minimum values, standard errors and standard deviations for each group are shown in Table 1. The values obtained via the fracture loads (in newtons, N) were statistically compared using the Tukey-HSD multiple comparison procedure.

Table 1. Mean and range values for final failure force (newtons)

Zirconia	10	3292.82$^{(A)}$	192.78	60.96	3045.36	3565.32
Hybrid ceramic	10	2325.02$^{(B)}$	264.3	83.57	1985.35	2678.21
PEEK	10	2214.23$^{(B)}$	236.97	74.93	1932.86	2604.32

PEEK: Polyether ether ketone, (A, B): Represent a significant difference according to Tukey-honest significant difference test between the different fabricated crowns

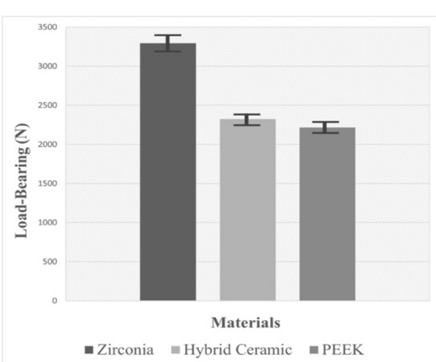

Figure 3. Bar graph for the fracture load of all three tested specimens groups

In terms of the fracture-resistance mean values, zirconia (3292.82 N±192.78 N, a characteristic fracture-load scale) was significantly higher than the others ($p<0.001$) were, but there was no significant difference between the hybrid ceramic (2325.02±264.3 N) and PEEK (2214.23±236.97 N) materials in terms of fracture resistance ($p=0.545$) (Figure 3).

Discussion

The purpose of this study was to evaluate the load-bearing capacities of PEEK, hybrid ceramic, and zirconia crowns fabricated using CAD/CAM. The data obtained in this study supported the null hypothesis. Many studies have investigated the maximum bite forces during mastication; in these studies, the mean maximum bite forces varied between 216 and 847 N; the highest bite force was in the first molar region: 807 N for men and 650 N for women (4,7,12). These values can increase to 965 N during the biting of an object (6). Therefore, it seems reasonable to assume that an initial fracture resistance of 1000 N would be required for a favorable clinical prognosis of the posterior region (7). In this study, the load-bearing values of all specimens exceeded 1000 N, so the load-bearing results showed that all groups had sufficient fracture strength against physiological occlusal forces.

As a result of continuous dental material research, PEEK can be engineered with a wide range of physical and mechanical applications. However, published peer-reviewed studies on PEEK's fracture resistance are scarce. Therefore, this *in vitro* test was performed, which included fracture load testing, to test PEEK's suitability as a material in the latter application. In addition, none of the published literature has compared the load-bearing capacities of PEEK, zirconia, and hybrid ceramic crowns.

In the present study, the CAD/CAM system was preferred, as it allowed for the use of high-quality materials, such as CAD/CAM-prefabricated blocks; this system also allowed for the standardization of manufactured crowns.

Alberto et al. (4) compared the load-bearing capacities of several ceramic materials using a three-point-bending test: two hybrids (Lava Ultimate and Vita Enamic), one feldspar (Mark 2), one lithium disilicate (IPS e-max), and one leucite-based material (IPS Empress). The study featured bars instead of crowns; the load-bearing capacities were found to be 4400 N for the IPS e-max, 2600 N for the Lava ultimate, 2500 N for the Vita Enamic, 2300 N for the IPS Empress, and 2200 N for the Mark 2. The IPS e-max material had a statistically significantly higher capacity than the other materials did, but there was no statistically significant difference between the two hybrid materials. De Kok et al. (8) reported that the fracture load of a monolithic zirconia crown was higher than that of a hybrid ceramic crown. These results are comparable to those in the present study.

Stawarczyk et al. (22) investigated the load-bearing capacities and failure types for three PEEK FDPs fabricated using various techniques. CAD/CAM milled PEEK (2354 N) had a higher mean fracture load than did those pressed from granular PEEK material (1738 N) ($p<0.001$). CAD/CAM milled FDPs and those pressed from PEEK/C pellets each showed spontaneous and brittle fractures near the pontic, without the deformation of the FDP. However, some plastic deformation of the FDP occurred without fractures.

Taufall et al. (21) compared the fracture loads of various veneered PEEK three-unit FDPs. Digitally veneered FDPs (1882-2021 N) had significantly higher fracture loads than the remaining conventional veneering groups did (1008-1229 N) ($p<0.001$).

In another study, Stawarczyk et al. (20) reported that three-unit PEEK FDP copings experienced plastic deformation at 1200 N and fracture loading at 1378 N. In the presented results, which are parallel to the results of Stawarczyk et al. (20), the PEEK crowns showed plastic deformation without breaking completely. The presumed reason for this is that PEEK has a low Young's modulus (3-4 GPa) and great material compared with other conventional materials, such as zirconia (E-modulus 210 GPa) (27). The low level of the elastic modulus of PEEK material is thought to provide insufficient support and to generate more stress on the surrounding structure (28).

The load-bearing testing of new crown materials for FDPs can contribute to decisions on clinical applicability, thereby reducing the risks for participants the least in subsequent clinical trials. In this study, the load-bearing capacities of the samples were determined by using a universal testing device. However, the physiological tangential movement of the abutment teeth in the experiment has not been modeled, and therefore, the load bearing test allows for the comparison of various coating materials, but with limited clinical relevance. Despite load-bearing standardization, a different loading and wear condition can occur under clinical loading conditions.

A further limiting factor of the significance of this study is the fact that no cyclic and thermomechanical loading was used on the universal testing device. The only data obtained from a specially published non-peer-reviewed dental manufacturing report showed that there is some reduction in the relative fracture load after the fatigue test. However, such tests are beyond the scope of this initial applicability and screening study (22).

It has been suggested that test specimens should have the same critical defects as the crowns produced for clinical use and that environmental effects should be reflected in the laboratory settings (29). However, further research is required for longitudinal clinical aging data, or at least for trends, with additional aging through chewing simulation or thermal cycling.

Although dental hard tooth tissue has a lower elastic modulus than zirconia does, the base model made of zirconia does not reflect the actual strength distribution associated with crowns cemented on natural teeth. As the modulus of the elasticity of the abutment increases, the fracture resistance of the restoration increases (30). The cement may absorb the applied forces. This lack of cement might have created inferior bending forces and weakened the damping effect. In this study, the specimens were not cemented on the zirconia model. In addition, the possible effect of cement use on the load-bearing capacities of PEEK crowns should be tested in further studies.

Conclusion

Long-term investigations and advancements in PEEK fabricated using CAD/CAM processing are not still warranted. This study showed that the load-bearing capacity of PEEK was lower than that of zirconia and was similar to that of hybrid ceramic. All three crowns were successful against physiological occlusal forces, and in an *in vitro* study, it was concluded that PEEK could be an alternative crown material for FDPs. Despite the limitations of *in vitro* studies, this result is promising in that clinical conditions. However, it is necessary to investigate the mechanical resistance of these crowns under clinical loading conditions.

Ethics

Ethics Committee Approval: The ethics committee approval was not necessary since the study was *in vitro*.

Informed Consent: Externally and internally peer reviewed.

Peer-review: Externally peer-reviewed.

Author Contribution

Surgical and Medical Practices: B.K.T., E.A., E.G.B., Concept: B.K.T., E.G.B., Design: B.K.T., E.G.B., Data Collection or Processing: B.K.T., E.A., E.G.B., Analysis or Interpretation: B.K.T., E.A., E.G.B., Literature Search: B.K.T., E.A., Writing: B.K.T., E.G.B.

Conflict of Interest: No conflict of interest was declared by the authors.

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