Fracture Resistance of Titanium, Zirconia, and Ceramic-Reinforced Polyetheretherketone Implant Abutments Supporting CAD/CAM Monolithic Lithium Disilicate Ceramic Crowns After Aging
Saadet Sağlam Atsü, DDS, PhD1/M. Emin Aksan, DDS2/Ali Can Bulut, DDS, PhD3

Purpose: The purpose of this study was to compare the fracture resistances and the fracture types of titanium, zirconia, and ceramic-reinforced polyetheretherketone (PEEK) implant abutments supporting computer-aided design/computer-aided manufacturing (CAD/CAM) monolithic lithium disilicate ceramic crowns after in vitro dynamic loading and thermocycling aging. Materials and Methods: Three implant abutment (SKY Implant) groups—titanium (group Ti, control); zirconia with titanium base (group Zr); and ceramic-reinforced PEEK (BioHPP) with titanium base (group RPEEK); n = 12 each—were used. Thirty-six CAD/CAM monolithic lithium disilicate crowns (IPS e.max CAD) in the form of a maxillary central incisor were cemented with Panavia V5 on the abutments. The specimens were subjected to dynamic loading and thermocycling. Fracture resistances of the restorations were tested with a universal testing machine (0.5 mm/min), and their fracture patterns were analyzed. One-way analysis of variance (ANOVA) and Tukey post hoc test were used for statistical analyses (α = .05). Results: All samples survived after aging. The fracture strength values (mean ± standard deviation) of the groups were as follows: group Ti, 787.8 ± 120.9 N; group Zr, 623.9 ± 97.4 N; and group RPEEK, 602.9 ± 121 N. The fracture strengths were significantly higher in group Ti compared to groups Zr and RPEEK (P = .001). No significant difference was observed between groups Zr and RPEEK. Failures generally occurred due to fracture of the screw in group Ti, abutment and crown in group Zr, and crown in group RPEEK. Conclusion: Ceramic-reinforced PEEK abutments may be an alternative to zirconia abutments with a titanium base for single-implant restorations in the anterior region. However, there is need for further in vitro and clinical studies to evaluate the long-term performance of ceramic-reinforced PEEK abutments.

Keywords: ceramic-reinforced polyetheretherketone, chewing simulator, dental implant abutments, fracture resistance, lithium disilicate crowns, titanium, zirconia

Both clinicians and patients increasingly prefer a single implant-supported crown for replacing a missing tooth. Long-term clinical trials show that the survival rate of dental implants is very good in treatment of single-tooth failures. The long-term success of implant treatment is affected by the osseointegration as well as the prosthetic supra-construction, ie, implant-abutment-crown complex, which must be consistent with the surrounding peri-implant tissues and the rest of the dental arch.

Implant abutments are usually fabricated from commercially available pure titanium since it has well-documented biocompatibility and mechanical properties. Even though production methods and designs of titanium abutments have been improving continuously, their metallic colors may still shine through the mucosa and impair the esthetic outcomes. Even when titanium abutments are placed subgingivally, their gray zone causes an unnatural bluish appearance on the soft tissues. All-ceramic abutments have been suggested to improve the esthetic appearance of single implant restorations. A ceramic abutment material that has better physical properties (yttria-stabilized zirconia dental implant abutment) improves
the gingival discolorations that occur when titanium abutments are used for patients who have thin soft tissue. Nonetheless, the type and structure of the implant-abutment connection might have a substantial influence on the stability and fixation of brittle ceramic abutments. Designs of implants include different types of implant-abutment connections. Zirconia abutments combined with titanium bases have much higher fracture strengths than pure zirconia abutments, and two-piece zirconia abutments may be used as an alternative to titanium abutments for single-implant restorations in the anterior region.

Polyetheretherketone (PEEK) is a high-performance thermoplastic polymer, and PEEK-based materials have been used in orthopedics, medicine, and dentistry because of their features such as biocompatibility, elastic modulus comparable to bone, and reduced stress shielding. On the other hand, high-performance polymers such as modified and reinforced PEEK that is based with 20% ceramic fillers have been increasingly used in the field of dentistry. Its 4-GPa modulus of elasticity is similar to bone, and it is highly biocompatible with soft tissues. The use of this white polymeric material has the advantages of preventing allergic reactions, good abrasion resistance, good polishing ability, and low plaque retention. For dental applications, ceramic-reinforced PEEK materials have been developed to improve the mechanical properties and colors of the restorations. They are fabricated either with computer-aided design (CAD) and computer-aided manufacturing (CAM) or with compression-molding. Titanium adhesive bases that have patient-specific abutment systems may be appropriate for anterior applications as mentioned in a study.

The use of ceramic-reinforced PEEK in dentistry is rather new, but it has been increasingly used in the last couple of years, especially for prosthetics such as crown and implant frameworks, telescopic crowns, resin-bonded fixed partial dentures, and removable partial dentures. Clinically, it was reported that ceramic-reinforced PEEK material used for fabrication of endocrowns, resin-bonded fixed partial dentures, removable partial dentures, and All-on-4 implant frameworks had promising results for 12 to 24 months follow-up. Nevertheless, limited information is available about ceramic-reinforced PEEK implant abutments. The purpose of this study was to compare the fracture resistances and fracture patterns of titanium, zirconia (on titanium base), and ceramic-reinforced PEEK (on titanium base) abutments restored with CAD/CAM monolithic lithium disilicate crowns after in vitro dynamic loading in a chewing simulator, and thermocycling aging. The tested hypothesis was that the fracture resistances of crowns on different implant abutments would not differ significantly.

**MATERIALS AND METHODS**

Thirty-six commercially available titanium (Ti) and zirconia (Zr) implant abutments (SKY implant) and ceramic-reinforced PEEK implant abutments (BioHPP, SKY implant) with a diameter of 3.5 mm, a length of 9.0 mm, and an internal hexagonal length of 2.2 mm were divided into 3 groups of 12 specimens each, by the abutment material as follows: group Ti, titanium abutment (control); group Zr, zirconia abutment with titanium base; and group RPEEK, ceramic-reinforced PEEK abutment with titanium base. All abutments were screw-retained (Fig 1).

In group Ti, the abutments were made from grade 4 Ti. There were two-piece hybrid abutments in group Zr. Each abutment was formed from a prefabricated all-zirconia coping that was adhesively cemented to a prefabricated titanium base (Bredent) using a dual-cure composite cement (DTK adhesive, #458080, Bredent). Group RPEEK consisted of prefabricated two-piece reinforced PEEK abutments produced by pressing ceramic-reinforced PEEK on a titanium base without adhesive cementation. The implant analogs (Ti grade 5) with diameter of 4 mm and length of 14 mm were embedded in an autopolymerizing polyester resin (Technovit 4071, #R010040) with an elastic modulus of 2.6 GPa to imitate an elastic reaction of the surrounding bone during loading. In order to standardize the dynamic loading of the specimens, the analogs were positioned in an embedding autopolymerizing resin at an angulation of 30 degrees to the vertical plane, which was designed to simulate occlusal loads, with the help of a metal cover, which stabilized the angle (Fig 2). Then, all abutments were fixed to the analogs with titanium screws using a torque of 25 Ncm according to the manufacturers’ recommendations. Torque wrenches were used to achieve a stable implant-abutment complex. Ten minutes later, the same tightening torque was applied once more to compensate for the loss of preload. The screw cavities were filled with Teflon tape and fluid composite (FiltekUltimate; #8B0009, 3M ESPE).

For the fabrication of 36 identically shaped monolithic crowns of a permanent maxillary central incisor from lithium disilicate (IPS e-max CAD, #U17559, Ivoclar Vivadent), CAD/CAM software (3Shape Dental System) was used. All crowns were standardized in terms of their external shape (height of 11 mm and width of 8.5 mm). The internal design of the crowns was made to fit the abutment surface precisely in all abutment groups. A shoulder margin was used for the crowns according to the abutment manufacturing.

Before cementation of the restorations, proper surface treatment of each material was performed in accordance with the manufacturers’ instructions (Table 1). The crowns were cemented using adhesive resin cement...
(Panavia V5, #000002, Kuraray Noritake Dental) under 50-N constant pressure for a 3-minute settling period on the chewing simulator. After excess cement was removed, light polymerization (Elipar S10, 3M ESPE) was applied for 30 seconds from the labial and palatal sides. The specimens were maintained at 37°C for 24 hours until the dynamic loading test.

All specimens were exposed to $4.8 \times 10^5$ loading cycles using 100-N dynamic loading force and 1.6-Hz chewing frequency in a computer-controlled dual-axis chewing simulator (Chewing Simulator CS-4, 5D Mechatronik) for simulating chewing for 2 years of clinical service (240,000 to 250,000 masticatory cycles in a chewing simulator correspond to 1 year of clinical service). A corrosion-free stainless-steel ball of 6-mm diameter was used as an antagonist. The specimens were loaded at a 30-degree angle of the palatal surface of the crowns, 3 mm below the incisal edge. In order to simulate the oral cavity's wet conditions and to subject the ceramic to a wet environment, all specimens were soaked in distilled water at room temperature during the whole period of the test.

During dynamic loading, all samples were controlled twice a day for failures. After the dynamic loading test, all samples were checked by a stereomicroscope (Carl Zeiss) with a magnification of $\times 12.5$ to detect any crack or fracture of the ceramic, or screw loosening that could be defined as failure. Then, all surviving specimens were subjected to thermocycling between 5°C and 55°C in 30-second cycles for a total of 2,000 cycles using a thermocycler (Esetron Smart Robotechnologies). The time interval between two baths was adjusted to 15 seconds. After thermocycling, the specimens were examined by a stereomicroscope (Carl Zeiss) with a magnification of $\times 12.5$. The specimens that survived without ceramic fracture, screw loosening, abutment or crown fracture, or any other deformation after aging were tested for maximum fracture strength using compressive load in a universal testing machine (Lloyd LRK 10 Plus). The load was applied at an angle of 30 degrees to the long axis of the implants to simulate a clinical occlusal force. Dynamic loading was applied (with a crosshead speed of 0.5 mm/min) on the spherical loading stamps that were centrally positioned at the same contact point. To ensure stress was distributed evenly, a small piece of tin foil with a thickness of 0.5 mm was placed on the crowns. Compressive loading continued until failure (a sudden reduction in force, or deflection of 3 mm was considered as fracture) (Fig 3). The fracture loads were recorded by software.

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**Table 1** Surface Treatments of the Materials Used

<table>
<thead>
<tr>
<th>Material Restoration</th>
<th>Surface treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium abutment</td>
<td>Airborne-particle abrasion with 110 µm Al₂O₃ at 2 bars from 15-mm distance for 10 s. Excess particles removed with ultrasonic bath including 96% ethanol for 10 min. Silane applied for 30 s and air dried.</td>
</tr>
<tr>
<td>Zirconia abutment</td>
<td>Airborne-particle abrasion with 110 µm Al₂O₃ at 2 bars from 15-mm distance for 10 s. Excess particles removed with ultrasonic bath including 96% ethanol for 10 min. Silane applied for 30 s and air dried.</td>
</tr>
<tr>
<td>Ceramic-reinforced PEEK abutment</td>
<td>Airborne-particle abrasion with 110 µm Al₂O₃ at 2 bars from 15-mm distance for 10 s. Excess particles removed with ultrasonic bath including 96% ethanol for 10 min. A special composite and PMMA primer mixture (Visio.link) applied for 10 s, and polymerized for 90 s.</td>
</tr>
<tr>
<td>Crown</td>
<td>Etched with 9.5% hydrofluoric acid for 30 s, rinsed for 60 s, and air dried. Silane applied for 30 s, and air dried.</td>
</tr>
</tbody>
</table>

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The location and mode of failure for each test specimen were recorded by examining them visually with the help of a LED light microscope (Carl Zeiss) with a magnification of $\times 12.5$. After the fracture resistance tests, the failure types were observed and categorized as follows: score 1, only crown fracture; score 2, abutment and crown fracture; score 3, screw fracture and deformation of the implant connection segment of the abutment without any destruction in the crown; score 4, screw and titanium sleeve fracture without crown fracture; score 5, separation of the abutment-crown complex from the titanium base.\textsuperscript{5,11,40,44,45}

Normality distribution was tested using the Shapiro-Wilk test, and the tests revealed that the data were distributed normally. A one-way analysis of variance (ANOVA) and the Tukey post hoc test were used to assess the significance of the differences in the fracture strengths of the groups ($\alpha = .05$). Statistical analyses were made using software (IBM SPSS Statistics V22.0, IBM Corp).

**RESULTS**

The samples did not show any failure such as screw loosening, screw breakage, and crown fracture after chewing simulation and thermocycling. This study demonstrated statistically homogenous inner-group results for all tested specimens. The results of the one-way ANOVA revealed that the fracture strengths were significantly different among the groups ($df = 35$, sum of squares $= 672,383.9$, $F = 9.513$, $P = .001$). The mean fracture strength values and standard deviations (SDs) of the groups are listed in Table 2. The mean fractures and SDs were 787.80 ± 120.95 N for group Ti, which showed the highest mean fracture resistance. It was followed by 623.93 ± 97.44 N for group Zr, and 602.93 ± 121.03 N for group RPEEK. Group Ti showed statistically significant differences from the other two groups ($P = .001$), while no significant difference was found between groups Zr and RPEEK.

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SD</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>787.80\textsuperscript{a}</td>
<td>120.95</td>
<td>546</td>
<td>943.67</td>
</tr>
<tr>
<td>Zr</td>
<td>623.93\textsuperscript{b}</td>
<td>97.44</td>
<td>446.45</td>
<td>761.12</td>
</tr>
<tr>
<td>RPEEK</td>
<td>602.93\textsuperscript{b}</td>
<td>121.03</td>
<td>418.65</td>
<td>770.1</td>
</tr>
</tbody>
</table>

The values with the same superscript do not display significant difference ($\alpha = .05$).

**DISCUSSION**

The implant abutments used in the treatment of the anterior region play an extremely important role in terms of esthetics and biomechanical features. For this reason, being able to use alternative materials such as gold, zirconia, alumina, lithium disilicate, and polymeric materials instead of titanium in implant abutment applications is highly desirable. There are studies that compare the fracture resistance of titanium abutments

<table>
<thead>
<tr>
<th>Fracture type</th>
<th>Ti % (n)</th>
<th>Zr % (n)</th>
<th>RPEEK % (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score 1</td>
<td>33.3 (4)</td>
<td>8.3 (1)</td>
<td>58.4 (7)</td>
</tr>
<tr>
<td>Score 2</td>
<td>0 (0)</td>
<td>58.4 (7)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Score 3</td>
<td>66.7 (8)</td>
<td>25 (3)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Score 4</td>
<td>0 (0)</td>
<td>8.3 (1)</td>
<td>8.3 (1)</td>
</tr>
<tr>
<td>Score 5</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>33.3 (4)</td>
</tr>
</tbody>
</table>

$n = \text{number of groups (values in parentheses)}$; Score 1 = only crown fracture; Score 2 = abutment and crown fracture; Score 3 = screw fracture and deformation at the implant connection segment of the abutment without any destruction in the crown; Score 4 = screw and titanium sleeve fracture without crown fracture; Score 5 = separation of the abutment-crown complex from the titanium base.
with or without restorative material (crown) to zirconia abutments, metal-ceramic custom abutments, \textsuperscript{46} alumina abutments, \textsuperscript{11,47,48} lithium disilicate abutments, PEEK abutments, \textsuperscript{16} and one- or two-piece abutments. However, there is no information regarding in vitro mechanical performance of ceramic-reinforced PEEK abutments. The hypothesis of this study was that the fracture resistance of titanium, zirconia (on titanium base), and ceramic-reinforced PEEK (on titanium base) abutments restored with monolithic CAD/CAM lithium disilicate all-ceramic crowns after artificial aging would not differ significantly between groups. The results showed that group Ti had significantly higher fracture resistance, whereas no significant differences were found between group Zr and group RPEEK ($P = .001$). This is in agreement with other studies, which report that titanium abutments restored with all-ceramic crowns exhibit significantly higher fracture strength compared to the ones restored with two-piece zirconia abutments.\textsuperscript{6,26,27}

The physiologic occlusal forces may range from 10 to 120 N during chewing or swallowing foods.\textsuperscript{49,50} In previous studies, maximum occlusal forces in the incisor area have been reported to range from 150 to 300 N\textsuperscript{51-53} and 90 to 370 N.\textsuperscript{22,54} In some studies, physiologic occlusal forces (200 N) that occur in the anterior region have been given for comparing fracture resistances of crowns. In the present study, all specimens showed failure loads over 418 N (minimum value is in Table 2) after chewing simulation and thermocycling. Thereby, they can resist clinical occlusal forces. These results are consistent with the previous in vitro studies on different designs of ceramic abutments.\textsuperscript{10,11,27,40,48} However, because of the lack of in vitro and clinical studies evaluating the strength of PEEK abutments reinforced with ceramic in the literature, the present study mainly focused on an in vitro study with dynamic loading and thermal cycle parameters that reflect short-term (approximately 2 years) clinical performance of recently
introduced ceramic-reinforced PEEK abutments. It should be noted that there is need for further in vitro and clinical studies that evaluate long-term clinical use.

Using abutment materials that are esthetically similar to tooth color is important. The gray color of titanium metal causes reflection from the gingiva, and the biomechanical properties of titanium are not similar to the natural tooth. With the lack of the proprioceptive mechanism at implant-supported restorations, abutments should have proper biomechanical properties to prevent resorption that may be formed in the bone as well as to prevent the fractures at abutments or abutment screws or the fractures of crown-prosthesis material. Ceramic-reinforced PEEK can be used as a dental implant abutment material because of its biomechanical features and biocompatibility. The information in the literature on the use of ceramic-reinforced PEEK and PEEK material for implant abutments is limited. In a case report, Al-Rabab'ah et al.55 used custom-made ceramic-reinforced PEEK abutments obtained by pressing on a titanium base for a patient with a single-tooth defect, and restored the problem with a monolithic lithium disilicate crown. At the 1- and 2-year follow-up controls, the bone and the soft tissue around the implant were stable, and it was possible to use the ceramic-reinforced PEEK material as an immediate permanent implant abutment since its mechanical properties were adequate.55 Rosentritt et al.15 subjected titanium-based personal zirconia and a group of experimental PEEK abutments to fatigue testing with a chewing simulator, and found that all experimental PEEK abutments displayed screw loosening between 0.4 \times 10^6 and 0.94 \times 10^6 cycles and then early failure due to screw fracture in some specimens. However, in that study, screw failure was frequently observed during dynamic loading in general, and it is reported that pre-loading loss occurred since the abutment screw was not retorqued after the first torquing. Still, the study reported that titanium-based personal PEEK abutments are promising for the anterior region, and are suitable for use. In another study comparing the fracture strengths of PEEK temporary implant abutments and titanium temporary implant abutments, temporary composite resin (Solidex) crowns with screw retention were produced in four different anatomies, maxillary central, lateral, canine, and premolar, on the abutments. It was found that the average fracture strength values of the crowns supported with PEEK abutments varied between 95 N and 486 N, while the fracture strength values of the crowns supported with titanium abutments varied between 387 N and 1,009 N.56 In another case report, Zoidis17 reported that ceramic-reinforced PEEK bases restored with high-strength PMMA veneers (novo.lign, Bredent) did not display any screw loosening, crown fracture, wearing, or straining in the control at the end of 2 years, and it can be used as a good treatment alternative in the All-on-4 treatment concept. Unlike these studies, a two-piece ceramic-reinforced PEEK implant abutment obtained by pressing on a titanium base was used in this study. For comparison, titanium abutment was selected as the control group, while another group of studies used titanium-based two-piece zirconia abutments, which have proven mechanical superiority to single-piece zirconia abutments. The results of this study show that group Zr (623.93 N) and group RPEEK (602.93 N) specimens have similar fracture resistances without statistically significant differences.

In fixed implant restorations, the cement-retained system has advantages compared with the screw-retained system in terms of passive compliance, esthetics, and load distribution during function. In addition, Zarone et al.57 reported that the load-bearing capacity of the cement-retained system was higher than that of the screw-retained system. In that study, the effect of different retainers (cement-screw) and connection types (internal-external) on the fracture strength was evaluated by in vitro modeling of centrally missing teeth with implant-supported metal crowns. Freitas et al.58 reported that the restorations with cement-retained internal connections had the highest fracture strength. Thus, in line with many other studies, cement-retained abutments with internal connection were used in this study.6,61

In implant-supported restorations, implant restoration material and esthetics in addition to implant abutments should be well evaluated during prosthetic treatment planning.6 Recent developments in high-strength ceramic materials and production techniques (CAD/CAM) have attempted to meet the optical and biomechanical expectations in implant-supported restorations.59 Glass ceramics reinforced with lithium disilicate (IPS e.max) can be produced by the lost wax and heat pressing technique or by milling with a CAD/CAM system. Their fracture strengths are between 300 and 400 MPa.6,60 The full anatomical e.max CAD crowns prepared in monolithic form provide fatigue resistance by increasing the mechanical stability. The ability of a single-piece structure to withstand higher forces enables this. Ceramic separation risk in veneer full-ceramic zirconia restorations especially in the anterior region increases the importance of glass ceramics reinforced with lithium disilicate in monolithic form. The studies that systematically review the clinical data involving at least 3 years of observations report that full-ceramic crowns have comparable survival rates compared with metal-ceramic crowns when they are used in the anterior region.7,61 Lithium disilicate glass-ceramic crowns have emerged as an alternative to the metal-ceramic crowns with metal abutments that are...
used as the gold standard in fixed prostheses with implant abutments due to their increasing clinical success.\textsuperscript{3,62} The information in the literature on monolithic lithium disilicate glass-ceramic crowns supported with different implant abutments is limited.\textsuperscript{6,60} For this reason, in this study, the abutments were supported with monolithic lithium disilicate glass-ceramic crowns produced using CAD/CAM techniques.

The choice of cement is an extremely important issue for both abutment and full-ceramic crown material. Phosphate monomer containing resin cement increases the bonding strength to the zirconia surface.\textsuperscript{63,64} The producer company (“Bredent” 2017b) suggests using resin cement containing acidic phosphate monomer (10-MDP), such as Panavia F 2.0 and Panavia V5, when lithium disilicate crowns are produced on ceramic-reinforced PEEK implant abutments. In many studies, such as in vitro fatigue tests or fracture strength tests of implant-supported crowns, the produced crowns were cemented to their implant abutments with resin cements such as Panavia F 2.0, Panavia F 21, and RelyX Ultimate (3M ESPE).\textsuperscript{10,15,24,60} In this study, lithium disilicate glass-ceramic crowns were cemented with Panavia V5 resin cement. The reason for this is that a catalyst that enables self-hardening so that Panavia V5 is not affected by the depth of polymerization of the light source has been developed, and it has been reported that Panavia V5 had better bonding strength compared with F 2.0.\textsuperscript{65}

In the literature, different fracture values are given for titanium and zirconium abutments under different testing conditions (with or without dynamic loading and thermocycling). Yilmaz et al\textsuperscript{66} compared five different zirconia abutments and reported that the average fracture load was 842 N for zirconia abutments with a titanium base. In that study, no aging test was performed, abutments in different lengths and diameters were used, and no crown was made. This could explain the lower fracture strength value (623.93 N) of the hybrid zirconia abutments observed in the present study. In a similar study, Kim et al\textsuperscript{66} compared fracture strengths of three different types of implant abutments (one-piece CAD/CAM abutment [Aadva, GC], titanium-based CAD/CAM zirconia abutment with friction-fit connection [Procera, Nobel Biocare], and titanium-based CAD/CAM zirconia abutment with adhesive connection [Lava Plus]) after aging with thermal cycles. The fracture strengths were found to be 484.6 N for the Nobel Biocare group, 503.9 N for the GC group, and 729.2 N for the Lava Plus group. Statistically, the fracture strength of the Lava Plus group was significantly higher than the other two groups. In that study, only thermocycling without dynamic loading was used and crown restoration was not made,\textsuperscript{66} which are the reasons for the different results observed in the present study. Att et al\textsuperscript{47,48} tested the static fracture resistance of different implant-supported all-ceramic restorations after chewing simulation. Ninety-six implants with internal connection design had titanium, alumina, and zirconia abutments. All abutments were restored with zirconia all-ceramic crowns. The specimens were exposed to $1.2 \times 10^6$ cycles under a load of 49 N in a chewing simulator. The mean fracture loads after aging were 1,310 to 1,344 N for titanium abutment–zirconia crowns, and 470 to 593 N for zirconia abutment–zirconia crowns, respectively. The different results of the present study may be attributed to using lithium disilicate crowns, two-piece zirconia abutments, and different dynamic loading parameters.

Fracture pattern is as important as achieving the desired fracture strength values for the restorations on implants. The fracture resistance results should also be coupled with the failure type analysis. Failures that can be corrected more easily than more catastrophic failures such as implant screw fractures, abutment fractures, and deformation at the implant-abutment connection site are becoming more important in the selection of abutment in the restorations on implants. In the present study, the fractures that occurred in the specimens after static loading were examined with a stereomicroscope in line with similar studies,\textsuperscript{11,26} and fracture types were classified according to the different classifications of similar studies.\textsuperscript{5,11,40,44,45} In the present study, the examinations of the fracture types with a microscope revealed the following (Table 3):

- e.max CAD specimens supported with titanium abutments had plastic deformation and screw fracture at the implant-abutment connection (66.67%) and crown fracture (33.33%).
- Titanium-based zirconium abutments had crown and abutment fracture (58.4%) and plastic deformation and screw fracture at the implant-abutment connection (25%).
- Titanium-based, ceramic-reinforced PEEK abutments had crown fracture (58.4%) and separation of the abutment-crown connection from the titanium base without crown, abutment, and screw fracture (33.3%).

The existence of only easily repairable failures such as crown fracture in the RPEEK group can be explained by the fact that the elastic modulus of ceramic-reinforced PEEK is closer to the natural tooth, and it has a more flexible structure than the crown on it.\textsuperscript{14} However, separation of the abutment-crown complex from the titanium base, which was another failure type of the hybrid ceramic-reinforced PEEK abutments, was observed only in this group. One of the failures of the hybrid zirconia abutments was screw fracture, and
this was consistent with many of the other studies. However, Martinez-Rus et al reported the existence of other failure types and abutment and crown fractures. Crown and abutment fractures in the zirconia abutment group may be explained by the fact that zirconia is more sensitive to thermocycling and phase changes in the material. The abutments in the titanium abutment group demonstrated mainly screw fractures similar to many of the other studies.

In this study, a higher number of chewing simulations and thermocycles might have been used. Even though this may be regarded as a potential limitation, it should be taken into consideration that there are many studies in the literature that evaluate the fracture strengths of implant-supported crowns without using any chewing simulations and/or thermocycles. Further studies comparing data of the fatigue resistances of titanium-based, ceramic-reinforced PEEK abutments as well as titanium-based zirconia abutments may provide additional insights.

**CONCLUSIONS**

Within the limitations of this study, promising fracture strengths and fracture types were found for the ceramic-reinforced PEEK abutments with a titanium base. The titanium abutments restored with monolithic lithium disilicate crowns had the highest fracture resistance (787.80 ± 120.95 N), whereas the zirconia (623.93 ± 97.44 N) and ceramic-reinforced PEEK (602.93 ± 121.03 N) abutments with a titanium base showed similar fracture resistances (P = .001). The ceramic-reinforced PEEK abutments had the potential to withstand maximum anterior occlusal forces, and also showed better fracture patterns than the zirconium abutments. However, further in vitro and clinical studies that evaluate the long-term performance of ceramic-reinforced PEEK abutments with a titanium base are needed before these abutments can be safely recommended as an aesthetic alternative for single-implant restorations in the anterior region.

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