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Investigation of Fracture Strength of Current Post Materials (Peek, Fiber, Cast Metal) in Different Ferrule Conditions

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Abstract

Aim: The fracture resistance of the post materials used nowadays significantly impacts the fracture type of the post material. The current study aimed to examine the impact of the fracture resistance of PEEK posts, whose use as a post material has not yet become widespread, on the fracture pattern that will occur. **Materials and Methods:** Sixty-six extracted upper central incisor human teeth were used in the study. Six groups of posts were produced from metal, fiber, and PEEK materials (n = 11). Afterward, the fracture resistance test was applied to the samples. Samples were classified according to fracture type as repairable or irreparable. The ANOVA and test were used in statistical analysis. Post-hoc tests were carried out using Tukey's and Tamhane's T2 tests. On the other hand, Pearson's chi-square test and the Fisher-Freeman-Halton test were conducted for comparisons between categorical variables. The statistical significance level was accepted as $p < 0.05$. **Results:** According to the fracture resistance test results, the groups where metal personal posts were used displayed higher fracture resistance in comparison with all other groups. According to the results of the optical microscope examination, the incidence of repairable fractures was significantly higher in the PEEK post group with ferrule preparation ($p < 0.05$). No significant difference was identified between the fiber and PEEK post groups with ferrule preparation ($p > 0.05$). **Conclusion:** In the absence of the ferrule effect, fractures are catastrophic, regardless of the material used. The use of PEEK as a post material contributes to keeping fractures at a repairable level.

Keywords

Component, Formatting, Style, Styling, Insert

1. Introduction

Numerous factors such as the amount of remaining tooth tissue, the treatment procedure applied, the type of material applied, and the position of the current tooth on the dental arch impact the prognosis of endodontically treated teeth [1]. When coronal tissue loss is 50% or more, post-core treatment can be applied to ensure the continuity of remaining tooth tissues [2]. Furthermore, it is known that the ferrule effect and the amount of remaining tooth tissue also increase the tooth's resistance to fracture [3] [4]. A ferrule is defined as a vertical band surrounding the tooth within the tooth structure in the gingival region in crown preparation [5]. Performing a ferrule preparation around the remaining tooth tissues and creating a ferrule effect can be effective in reducing intracanal stress and preventing possible root fractures [6]. Previous studies in the literature have shown that even a 1 mm ferrule effect is the minimum width that is effective in stabilizing the restoration. In their study, Tjan and Whang observed a significant difference between ferrule widths of 1 mm, 2 mm, and 3 mm [7]. The research by Fontana *et al.* found that the effect of a 0.5 mm ferrule width was low [8]. Studies have demonstrated that ferrule height is more important in terms of durability. It was reported that the minimum ferrule height required for post-core restorations was 1.5 - 2 mm [5]. In addition to the amount of remaining tooth tissue, the type and material selection of the restoration to be used are also important for the prognosis of endodontically treated teeth [9]. Nowadays, dentistry mainly focuses on two types of post systems. One of these is prefabricated post systems. The other one is metal cast post-cores [10]. These systems have various advantages and disadvantages over each other. The use of prefabricated fiber posts causes the chewing forces on the teeth to not be distributed evenly [11]. The static or dynamic behavior of resin-fiber posts also depends on their composition (fiber type and density), production technique, and the quality of the resin-fiber interface [12].

Elastic modulus values of metal and ceramic posts produced in accordance with the root and canal structure (110 Gpa for titanium, 200 Gpa for zirconium, and 300 Gpa for aluminum oxide) are higher compared to dentin [13]. Fiber post systems are preferred for clinical use due to numerous disadvantages of cast post cores, including metallic color, corrosion, decementation, loss of retention, and root fracture formation [8]. Although fiber posts have many superior features in comparison with metal posts, they cause mechanical stress on the cervical dentin and restoration border and do not strengthen the tooth structure [14]. Moreover, although they have a lower modulus of elasticity (45.7 - 53.8 GPa) compared to metal posts (95.0 - 110.0 GPa), the value in question is still almost three times that of dentin (18.6 GPa) [15]. Polyetheretherketone (PEEK) represents a semi-crystalline, high-performance thermoplastic polymer that is becoming increasingly popular in dentistry because of its mechanical, thermal, and chemical properties, fatigue resistance, low water absorption, and excellent biocompatibility [16]. Its mechanical properties, such as elastic modulus, can be adjusted by changing the filling content and incorporating inorganic fillings [17]. The elastic modulus of PEEK close to dentin allows it to function as a stress breaker, reducing the forces transferred to restorations [18]. This is a very important advantage because it has been indicated that stress distribution is homogeneous when dental materials have an elastic modulus similar to that of dentin [18]. Additionally, the presence of radiolucency makes it possible to evaluate treatment procedures step by step [19]. However, there are very few studies evaluating PEEK, a high-performance polymer, as a post material on human teeth using appropriate surface treatments and resin bonding systems.

The present research aims to examine the contribution of the ferrule effect to the fracture resistance of posts prepared with metal, glass fiber, and PEEK materials.

There are two hypotheses in this study. The first is that PEEK post groups display significantly higher fracture resistance than other groups. The second is that the fracture resistance of the PEEK post group without ferrule preparation does not differ significantly from the other experimental groups with ferrule preparation.

2. Materials and Method

The number of teeth to be utilized in the research was calculated with G*power software based on the parameters utilized in a previous study. The sample size was computed for the cases where results of the fracture resistance test for the "cast post core" control group used in the study, performed without a ferrule and with a 1 mm ferrule, were 339 ± 153 and 575 ± 2.4 [8]. In this case, it was calculated that each group should include 11 teeth at an 80% power and a 95% confidence level. Considering the need to standardize the extracted teeth and possible fractures during the ferrule preparation stage, 15 upper central first incisors were allocated for each group. Possible fractures, cracks, and morphological defects were examined with a magnifying glass (×3.5; Q-Optics radiant). It was observed radiologically and clinically that the 90 human upper first incisors provided had a single and straight canal morphology, no caries, no previous endodontic treatment, and no internal or external resorption. All teeth allocated were cleaned of soft and hard tissue residues and kept in 0.1% thymol solution for 3 months (Thymol; Supelco®, Sigma_Aldrich Chemie GmbH, St. Louis, Missouri, USA). To avoid tooth size differences between the groups, the mesio-distal and vestibulo-lingual dimensions of the teeth were measured with a dental caliper (Insize, 1205-2002S). It was confirmed that the data were distributed homogeneously. Then, 66 teeth were randomly distributed into 6 subgroups. **Table 1** presents the group diagram.

To create a simulation of the periodontal ligament, the modeling wax used in the Delrin (polyoxymethylene) model was liquefied at 65˚C. The wax was applied to the root of each tooth with a thickness of 0.2 mm (average periodontal ligament thickness), starting from 3 mm below the crown. Then, the applied

Table 1. Study design.

Post type	Ferrule thickness	Group code
Metal	Without ferrule preparation	CP-0
Metal	Ferrule effect with a height of 2 mm and a thickness of 1 mm	CP-1
Fiber	Without ferrule preparation	FP-0
Fiber	Ferrule effect with a height of 2 mm and a thickness of 1 mm	FP-1
PEEK	Without ferrule preparation	PP-0
PEEK	Ferrule effect with a height of 2 mm and a thickness of 1 mm	PP-1

tooth model was embedded in the Delrin cylinder. The Delrin model dimensions were prepared as a height of 20 mm and a diameter of 25 mm. The teeth embedded in the prepared Delrin model were removed, and the wax layer around the root was scraped. Then, the impression material (Impregum F, 3M-ESPE, Seefeld, Germany) prepared in line with the manufacturer's instructions was placed into the artificial alveolar socket. The dental impression material was placed into the applied alveolar socket, and the excess impression material was removed. An elastomeric impression material was utilized to mimic the periodontal ligament (Impregum F, 3M-ESPE, Seefeld, Germany).

2.1. Endodontic Treatment Procedure

The crowns of the teeth were removed using a diamond separating disc attached to a high-speed handpiece, leaving a root length of 15 mm. Teeth with a single, straight root canal with root lengths of at least 13 mm were used. A standard endodontic protocol was applied [20]. The canals were enlarged to the width of Protaper F3 with the help of Protaper hand-held files. During the preparation, continuous irrigation with 5.25% NaOCl (Sodium hypochlorite) solution and physiological saline was provided. Coronal preparation was completed with Gates Glidden No. 3, 4, and 5 (Dentspy-Maillefer), and physiological saline was used as the final washing solution. Afterward, it was ensured that the canals were clean and dry with the help of paper points. Canal filling was performed by applying gutta-percha, which is compatible with hand-held Protaper canal files, into the canal using the cold lateral condensation technique. To fill possible irregularities during canal filling and fill in the gaps between gutta-percha, a canal filling paste (Sealapex, Kerr) was applied to the canal space by dipping it on the gutta-percha surfaces. Isolation of the canal filling was achieved using a temporary restoration material (Cavit-G; 3M ESPE). The samples were stored at 37˚C and 100% humidity for one week.

2.2. Intracanal Post Slot Preparation

The length of the post slot was designed as 9 mm for groups without ferrule and

11 mm for groups with a 2 mm ferrule height. For groups FP-0 and FP-1, the preparation was first carried out using No. 4 Largo burs (Dentsply Maillefer) and completed with standard burs of the Whitepost DC No. 2 fiberglass post system (FGM). For groups CP-0 and CP-1, the post space was prepared with No. 3, 4, and 5 Largo burs (Dentsply Maillefer). In PEEK post slot preparation, the protocol applied in fiber post slot preparation was repeated. For groups without ferrule preparation, the crown preparation was flat-ended and 3 mm above the enamel-cement junction.

2.3. Ferrule Preparation

In the study, ferrule preparation with a height of 2 mm and a width of 1 mm was applied to the groups for which ferrule preparation was planned. For groups CP-1, PP-1, and FP-1, the ferrule was prepared manually using a diamond bur (No. 3216, KG Sorensen, Barueri, Brazil) connected to a high-speed water-cooled micro motor (Extra Torque 605C; Kavo do Brasil, Joinville).

2.4. Post Production

For cast and PEEK posts, plastic posts (Pinjet Angelus, Londrina, Parana Brazil) were adapted to the root canal by coating them with chemically activated acrylic resin (Bosworth Trim Plus Company, Skokie, IL, USA). Acrylic resin-coated plastic posts were delivered to a commercial laboratory for casting for metal post groups. Ready-made prefabricated fiber posts were used as fiber posts. PEEK posts were produced by transferring the indirect measurement taken inside the canal to the digital environment with a digital scanner using the CAD/CAM (Shining 3D EinScan H 3D Scanner) system and milling it from ready-made prefabricated blocks (Whitepeaks Dental Solutions) in the CAD/CAM device (VHF K5). Table 2 contains the contents and manufacturer information of the post types utilized in the research.

Table 2. Production method and contents of post materials.

Group number	Production method	Post content
CP-0	Lost-wax technique	Ni-Cr alloy, Ramanium CS; Dentaurum, Pforzheim, Germany
CP-1	Lost-wax technique	Ni-Cr alloy, Ramanium CS; Dentaurum, Pforzheim, Germany
FP-0	Prefabricated	White post DC No: 2 FGM
FP-1	Prefabricated	White post DC No: 2 FGM
PP-0	Milling CAD/CAM system	CopraPeek Light PEEK-Blank Art.Nr.E0198201White Peaks Dental
PP-1	Milling CAD/CAM system	CopraPeek Light PEEK-Blank Art.Nr.E0198201White Peaks Dental

2.5. Surface Treatments

All samples were cleaned using 70% ethanol after production and dried. Then, phosphoric acid (K Etchant GEL L; Kuraray, Umeda, Osaka, Japan) was applied to the fiber post surfaces following the manufacturer's instructions. After 5 s of acid treatment, the fiber surfaces were rinsed with water. Surface treatment for the PEEK post groups was achieved by applying 98% sulfuric acid to the material surface for 60 s. After the acidification process, the materials were washed with distilled water for one minute and dried. Surface treatments for cast posts were performed by spraying Al_2O_3 particles with a particle size of 15 nanometers onto the post surface with a pressure of 50 MPa for 15 s.

2.6. Surface Measurements and Surface Observation

The surface roughness (Ra) of the surface-treated post materials was measured with a non-contact profilometer (3D non-contact profilometer Kla Tencor Stylus Profiler P7). After the surface treatment, the structural surface topography of each group was observed under a scanning electron microscope.

2.7. Application of Post Materials into the Canal and Their Cementation

The root canal and coronal sections were acidified using 37% phosphoric acid (Condac 37, FGM), washed with distilled water, and dried with paper points. Adhesive Ambar (FGM) was applied in line with the manufacturer's instructions. Finally, the posts were cemented with dual-cure resin cement (Allcem, FGM), which was also manipulated in line with the manufacturer's recommendations. They were then polymerized using a light device.

2.8. Core Production

Composite resin (Opallis, FGM) was used for core production. To standardize the core structure among all groups, a mold was created using a composite sample prepared with a transparent siloxane-based material (Dayson). Using the same siloxane mold for all samples, the core structure was adapted onto the post and photoactivated for 10 s.

2.9. Production and Cementation of the Crown Material

Zirconia substructure crowns suitable for the upper first incisor crown anatomy were produced for all groups (Upcera Dental Zirconia ST White) 37% phosphoric acid was applied to the tooth and composite core structure to ensure connection with the crown material for 15 s. The acid was removed by washing with air/water spray for 60 seconds, and the surfaces were dried. Adhesive Ambar (FGM) was applied to the acid-treated surfaces in line with the manufacturer's instructions. In the cementation of crown substructures, dual-cure resin cement (Allcem, FGM) was applied following the manufacturer's instructions. After polymerization for 1 minute under a 0.5 kg static pressure, photoactivation was provided from each angle for 10 s. The samples were left for 24 hours before testing.

2.10. Aging Procedure

After a 24-hour resting period, the samples were subjected to thermal cycling tests and chewing tests in an electromagnetic machine. The samples were aged by keeping them at 5˚C for 20 seconds and at 55˚C for 20 seconds in a machine (Acumen III; MTS Systems Corp.) simulating the oral environment and by subjecting them to 6000 thermal cycles, with 20 seconds between cycles, to correspond to a five-year service period in the mouth, and were then subjected to the fracture resistance test. The fracture types of the samples subjected to the fracture resistance test after aging were classified with the help of an optical microscope.

2.11. Fracture Resistance Test

A universal testing device (Model 4202; Instron) was utilized for the fracture resistance test. The samples were placed from the palatal region of the zirconia crown material at the level of the breaker tip, forming an angle of 135˚ with the long axis of the tooth. The fracture resistance test was conducted at a low speed (1 cm/min) (**Figure 1**). At the end of the test, each sample was examined with an optical microscope under ×10 magnification for the fracture mode. Root fractures were classified as catastrophic, in other words, requiring tooth extraction, or repairable fractures.

Figure 1. Fracture strength test.

2.12. Statistical Analysis

Analysis was performed with IBM SPSS 20 statistical analysis software. Data were presented as mean, standard deviation, median, minimum, maximum, percentage, and number. The normal distribution of continuous variables was examined with the Shapiro-Wilk W and Kolmogorov-Simirnov tests. In comparing continuous variables with more than two independent groups, the ANOVA test was conducted. After the ANOVA test, post-hoc tests were conducted using Tukey's test when the variances were homogeneous, and Tamhane's T2 test when the variances were not homogeneous. For comparisons between categorical variables larger than 2 × 2, Pearson's chi-square test was carried out when the expected value was (>5), and the Fisher-Freeman-Halton test was conducted when the expected value was (<5). The statistical significance level was accepted as $p < 0.05$.

3. Results

The maximum fracture resistance averages of 6 different experimental groups were higher than the maximum force values (286 N) given in the literature for the anterior region (Assif D, 1994). According to the findings of the fracture resistance test, the groups where metal personal posts were used (CP-0, CP-1) showed higher fracture resistance in comparison with all other groups. According to the ANOVA test results, the cast post samples (CP-1) with ferrule preparation showed significantly higher fracture resistance than the other groups ($p < 0.05$). Table 3 presents the statistical results of the fracture resistance test values according to ANOVA analysis.

There were significant differences between the groups in the statistical analysis based on the surface roughness characteristics of the posts. Fiber posts (FP-0

Table 3. ANOVA statistical results of the fracture resistance test.

Group number	Fracture resistance (Mean) ± SD; median (minimum-maximum)	F	P
CP-0	415.0300 ± 126.4174; 412.440 (182.3600 - 182.3600)^{A}		
CP-1	567.7564 ± 108.1213; 565.220 (362.7900 - 775.1300)^{B}		
FP-0	309.8100 ± 99.8239; 312.450 (163.5500 - 458.9000)^{A}		
FP-1	322.4682 ± 109.1813; 320.060 (141.5800 - 508.2200)^{A}	7.565	P < 0.01
PP-0	341.2164 ± 129.6218; 330.650 (120.5600 - 534.6500)^{A}		
PP-1	377.6036 ± 115.9855; 364.080 (173.4500 - 558.1500)^{A}		

The fracture resistance value of the CP-1 group differs statistically significantly from the other groups.

and FP-1) displayed significantly higher surface roughness values than all other groups ($p < 0.05$). PEEK post groups (PP-0 and PP-1) had significantly lower surface roughness values compared to all other groups ($p < 0.05$). Table 4 contains the statistical results of the surface roughness values of all post materials according to ANOVA analysis

Table 5 presents the results of analyzing fracture types according to the Fisher-Freeman-Halton test by examining the fracture types according to the level of repairability under the optical microscope as a result of the fracture test.

Statistical analysis of the fracture types of the samples subjected to fracture testing was performed under an optical microscope (×10). Significant differences were revealed between certain groups. The incidence of repairable type fractures in the PEEK post group (PP-1) with ferrule preparation was found to be significantly higher in comparison with the other groups (CP-0, CP-1, FP-0, and

Table 4. ANOVA test result of surface roughness values.

Group number	Surface roughness (Mean) ± SD; median (minimum-maximum)	F	P
CP-0	2.13 ± 0.13; 2.13 (1.91 ± 2.29)^{A}	314.321	P < 0.01
CP-1	2.14 ± 0.13; 2.15 (1.91 ± 2.32)^{A}		
FP-0	2.96 ± 0.08; 2.94 (2.88 ± 3.16)^{B}		
FP-1	2.96 ± 0.16; 2.94 (2.79 ± 3.21)^{B}		
PP-0	1.65 ± 0.08; 1.66 (1.53 ± 1.77)^{C}		
PP-1	1.64 ± 0.05; 1.65 (1.55 ± 1.73)^{C}		

Surface roughness differs significantly between peek fiber and cast post materials.

Table 5. Post-hoc statistical analysis of fracture repairability.

Group number	Mean ± SD	P	N
CP-0	2.13^{A}	<0.001	0
CP-1	2.15^{A}		2
FP-0	2.94^{A}		0
FP-1	2.94^{B}		8
PP-0	1.66^{A}		2
PP-1	1.65^{B}		9
Total	Repairable		21

Repairable fractures in FP-1 and PP-1 groups differ significantly from the other groups.

PP-0) ($p < 0.05$). Likewise, in the fiber post groups (FP-1) with ferrule preparation, the incidence of repairable fractures was found to be statistically significantly higher than in the other groups. No significant difference was identified between fiber (FP-1) and PEEK (PP-1) post groups with ferrule preparation ($p > 0.05$). **Figure 2** and **Figure 3** show the optical microscope image of the fracture lines under ×10 magnification. Upon examining the SEM images (×2000) of the samples, it was observed that groups PP-0 and PP-1 had acid erosion areas on the flat surface, unlike the other samples (**Figure 4**). When SEM images for groups CP-0 and CP-1 were examined, it was seen that the metal surface formed a recessed structure owing to Al_2O_3 particles and there were Al_2O_3 particles in the particulate structure on the surface. The fiber structure of the fiber post groups (FP-0 and FP-1) embedded in the resin matrix created recessed areas between the two recessed structures. Furthermore, there were particulate structures belonging to the dissolved resin component due to the effect of sulfuric acid on the fiber structure.

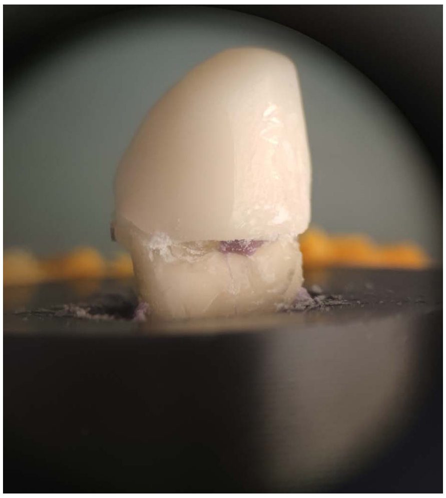

Figure 2. Repairable fracture.

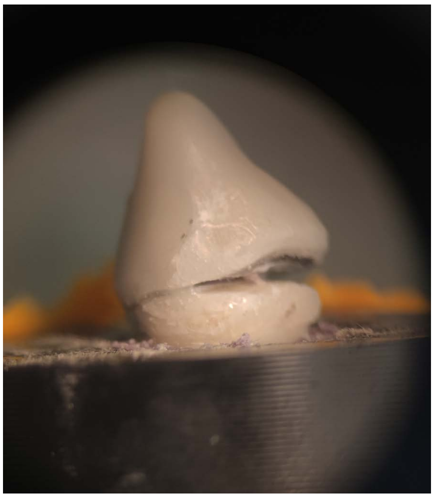

Figure 3. Catastropic fracture.

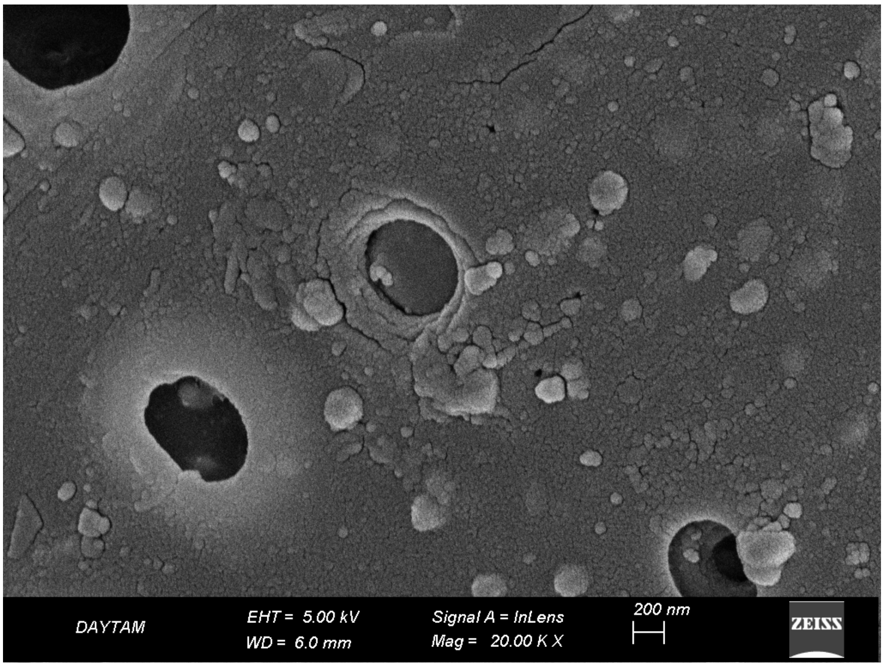

Figure 4. SEM image of peek post sample under 20,000 magnification.

4. Discussion

There are two hypotheses in the current study. The first is that PEEK post groups show significantly higher fracture strength compared to other groups. Since metal post groups (CP-0 and CP-1) displayed higher fracture resistance than the other post groups, the first hypothesis of the study was rejected. This was due to the fact that metal has less elastic capacity due to its high elastic modulus value (200 GPa) and transmits the force on the restoration directly to the dentin tissue [21].

The second hypothesis of the study is that the fracture resistance of the PEEK post group without ferrule preparation does not differ significantly from the other experimental groups with ferrule preparation. Since there was no significant difference between group PP-0 and groups FP-1 and PP-1, but group CP-1 had significantly higher fracture resistance compared to group PP-0, the second hypothesis of the study was also rejected.

The impacts of post core application on endodontically treated teeth on fracture resistance and fracture formation are affected by multiple factors. To determine the material indication appropriate for the case in post-core treatments, numerous factors should be considered. Hence, it becomes very difficult to identify a single type of material suitable for every clinical condition [22].

The connection of the post types used with the canal dentin tissue plays an essential role in the fracture resistance of the applied post treatment [23]. A good connection quality is crucial, especially for chemically cemented posts. A good connection with canal dentin increases fracture resistance [24]. SR (surface roughness) is an essential factor in the adhesive procedure and requires different surface treatment methods to increase the bonding area and micro-roughness of the dental material [25]. In our study, there were significant differences between the surface roughness values measured after surface treatments ($p < 0.05$). The surface roughness values measured for all experimental groups are compatible with the Ra values in the literature [26]. Considering the surface roughness values, the fiber post groups (FP-0, FP-1) displayed significantly higher roughness values compared to all other materials ($p < 0.05$). This may be due to the difficulty of surface treatment of metal posts and the chemically inert structure and low surface energy of PEEK post materials [27]. According to the study results, fiber posts displaying the highest surface roughness values showed the lowest values in the fracture resistance test. In accordance with the findings of the current work, it can be stated that increasing surface roughness does not have a direct positive impact on fracture resistance. As confirmed by SEM images, PEEK showed pits and pores dispersed with filling particles on the surface, as shown in other previous studies [28].

Regardless of all variables, first, the material to be used must have high fracture resistance beyond the maximum bite force applied by the anterior teeth. As seen from the results of the present research, all experimental groups displayed fracture resistance values higher than 222 N, which is the maximum bite force in the anterior region previously reported by Bakke *et al.* [29].

Considering the results of studies in the literature that do not include the ferrule effect, the fracture resistance values of metal, fiber, and PEEK posts differ [30]. Many studies have shown that the fracture resistance of cast metal posts is significantly higher compared to fiber posts [31]. In our study, no statistically significant difference was revealed between groups CP-0, FP-0, and PP-0 where there was no ferrule effect ($p > 0.05$). Metal posts exhibited higher fracture resistance than other groups, but this value was statistically insignificant. Similar to our study, a study in which bovine upper first incisors were used reported no significant difference in terms of fracture resistance between cast metal and glass fiber post types [32]. In line with the results of our research, many studies have reported that the type of material used does not have a statistical effect on fracture resistance when there is no dentin tissue above the alveolar bone level [8] [33].

Whereas there is a consensus in the literature that the fracture resistance of PEEK posts is lower compared to metal posts under conditions without the ferrule effect, studies on the fracture resistance of PEEK and glass fiber posts report different results [34]. According to the findings of our research, there is no significant difference in terms of fracture resistance between the glass fiber and PEEK post groups without ferrule preparation. However, it was observed that the fracture resistance values of PEEK posts were higher than those of glass fiber posts. In a study reporting similar results, the fracture resistance values of glass fiber and PEEK posts were compared. According to the study results, the fracture resistance of PEEK posts was found to be statistically higher [34]. Unlike the findings of our study, some studies report that the fracture resistance of PEEK posts is significantly lower compared to glass fiber posts [35]. Variations between articles reporting different results may be due to technical differences in the production stages of PEEK posts or variations in surface treatments and adhesive procedures applied.

According to the results of the groups with ferrule preparation, the ferrule effect increased the fracture resistance of all materials used. The above-mentioned result is compatible with many previous studies [33] ($p < 0.05$). Fracture resistance increased in all types of materials examined in the current research, but the only material that displayed a statistically significant difference was cast post cores. The aforesaid situation is compatible with the literature information [36]. A meta-analysis compared fiber and metal posts and concluded that metal cast posts showed high fracture resistance [37]. Many previous studies support the results obtained [38]. On the other hand, a study examining the fracture resistance of cast metal, glass fiber, and zirconia posts reported that glass fiber posts with composite core displayed the highest fracture resistance value [39].

In the literature, most authors reported that fiber posts display fracture resistance values increasing with the amount of remaining coronal dentin tissue [8]. There are not many studies on this subject in the literature regarding PEEK posts yet. However, the results obtained are similar to those for glass fiber posts [40]. In a study using extracted premolar teeth, in line with our study findings, the fracture resistance values of the PEEK post group were measured to be higher, but no statistically significant difference was revealed [21]. In another finite element analysis conducted in a similar manner, it was observed that the fracture resistance of PEEK posts was higher compared to fiber posts, but it was statistically insignificant [40]. However, the possibility of canal-specific production of PEEK posts and the possibility of producing them together with the core structure without the need to use composite cores require peek posts to be considered an important alternative to fiber posts [40]. Considering the increasing accessibility and decreasing cost of CAD/CAM systems, more clinical and laboratory studies on PEEK posts are needed.

Among the complications that may occur for a tooth with post core applied, the most difficult situation to repair is tooth fractures. The repair of a broken tooth is much more difficult than before restoration, and repair is impossible in cases where the fracture line extends below the alveolar bone level [41]. Similar to the results of previous *in vitro* and *in vivo* studies, fractures occurring in samples without the ferrule effect are mostly irreparable [6]. According to the findings of the current work, all fractures except two PEEK posts in teeth without ferrule preparation were catastrophic. Another study examined the fracture resistance of zirconia ceramic posts, fiber posts, and glass fiber-reinforced composite resin posts. Similar to the present research, it was determined that a catastrophic fracture occurred in all samples without ferrule preparation [42]. Another study examining the fracture resistance of titanium and glass fiber posts reported no difference in fracture types between the groups without a ferrule [43]. A study showed that in teeth where there was no ferrule effect and where glass fiber and cast metal posts were used, both post type restorations displayed similar survival after 3 years of clinical follow-up, and fractures were mostly catastrophic [44].

There is no common opinion in the literature about the post material that should be used under conditions where the ferrule effect cannot be achieved [33]. Although cast posts exhibit higher fracture resistance compared to other materials, it is known that they are associated with irreparable fracture types [37] [45]. The search for materials with high resistance to fracture forces but low potential to cause irreparable fractures continues. In the current study, the fact that a lower number of catastrophic failures were observed while achieving a higher fracture resistance suggested that PEEK posts might show higher clinical performance compared to fiber posts. In a study carried out to observe the impact of low elastic modulus on stress distribution, a finite element analysis was performed using PEEK, fiber, and cast posts. It was found that the stress areas created by the PEEK material on the root dentin were much more balanced in comparison with cast and glass fiber posts [46]. In this case, the use of PEEK posts can be considered a more advantageous option compared to previously tested materials. However, according to the test results acquired from the present study, the use of PEEK posts does not seem to be sufficient to prevent the formation of irreparable fractures. It would be beneficial to conduct *in vivo* studies on the restoration of real teeth with periodontal feedback mechanism using PEEK posts for providing more literature information on this subject.

Upon examining the groups with ferrule preparation in our study, it was revealed that the probability of catastrophic fractures was much higher in metal groups with high fracture resistance (CP-1) (81.1%), ($p < 0.05$). In previous studies, there is a consensus that metal posts, with or without the ferrule effect, cause catastrophic fractures in the root [47]. Repairable fractures observed in group CP-1 were not determined to be statistically significant ($p > 0.05$). In the literature, in line with the results we obtained, many studies do not find the impact of the ferrule presence on the fracture type of cast posts significant [32]. A study reported that high forces on metal posts are transmitted to the tooth structure and vertical fractures may occur due to the resulting wedge effect [48]. Unlike these studies, some studies also report that the fracture pattern of cast posts with the ferrule effect changes from vertical fractures to repairable fractures [32] [49] [50].

When the ferrule effect was present, the incidence of repairable fractures for fiber and PEEK posts (FP-1, PP-1) was revealed to be statistically significantly higher, unlike metal posts ($p < 0.05$). Many authors have reported similar results indicating that a minimum ferrule effect of 1.5 mm for fiber posts will significantly reduce the risk of catastrophic fractures [51] [52]. There is a prevailing opinion in the literature that the ferrule effect significantly reduces the risk of catastrophic fractures in fiber posts [53]. When studies on the fracture resistance of PEEK posts and fracture types are reviewed, there is a common opinion that the mechanical properties of PEEK posts are similar to those of glass fiber posts

[47]. However, there are very few studies on the fracture modes of PEEK posts under different ferrule conditions [47]. According to the results of these studies, ruptures resulting from connection failure at the cement interface occurred at a considerably higher level in PEEK post groups than in other post groups [47]. When the types of adhesive cement used in studies reporting failure due to loss of retention were examined, it was seen that they were self-etch cements [54]. The study by Benli *et al.* reported that PEEK posts cemented with 10-mdp-containing dual-cure resin after appropriate surface treatments exhibited considerably higher bonding strength in comparison with previous studies [53]. In the current study, cementation was performed with 10-mdp-containing dual-cure resin cement following the acid treatment recommended for PEEK surfaces. In our study, the incidence of repairable fractures in group PP-1 was similar to group FP-1 and significantly higher than in group CP-1 ($p < 0.05$). The incidence of repairable fractures was higher in group PP-1, but the difference between PP-1 and FP-1 was insignificant ($p > 0.05$).

A study where metal, glass fiber, and PEEK posts were applied into the maxillary incisor canal with a 2 mm ferrule support reported that the incidence of irreparable fractures in the teeth treated with the PEEK post group was significantly lower in comparison with the other groups [18]. Likewise, a study examining the fracture resistance of Ni-Cr, glass fiber, and PEEK posts found the incidence of repairable fractures to be statistically higher for PEEK posts [21]. The literature review showed that the number of published studies on the fracture resistance and fracture types of PEEK posts under different ferrule conditions was insufficient. There is a need for more *in vivo* and *in vitro* studies on this subject. The present research has some limitations:

The current research is an *in vitro* study and does not include many factors in the oral environment, particularly feedback mechanisms.

Zirconia crowns produced on composite cores were manufactured as a substructure design and are smaller than the actual crown dimensions.

A tensile test was not conducted to make a more meaningful interpretation of the adhesion from the measured surface roughness values.

5. Conclusions

The following conclusions were obtained within the limits of the present research;

1) Under conditions without the ferrule effect, the fractures observed are catastrophic, regardless of the material used.

2) The use of metal posts may be associated with an increased risk of vertical catastrophic root fractures.

3) In cases where there is no dentin tissue above the alveolar bone level, the use of PEEK posts is insufficient to prevent catastrophic fractures.

4) The use of PEEK as a post material contributes to keeping fractures at a repairable level.

5) Compared to metal posts, the incidence of repairable fractures in glass fiber and PEEK posts shows a statistically significant difference in cases where the ferrule effect is present ($p < 0.05$).

6) It was determined that the use of PEEK posts did not make a significant difference in the formation of repairable fractures for teeth that had completely lost all of their coronal walls ($p > 0.05$).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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