EFFECT OF DIFFERENT CANTILEVER LENGTH AND CONNECTOR DIMENSION ON THE LOAD-TO-FRACTURE OF CANTILEVERED POLY-ETHER-KETONE-KETONE (PEKK) FIXED DENTAL PROSTHESES

A Thesis

by

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ABSTRACT

Statement of Problem. Previous studies have not examined cantilever length nor cross-sectional dimension of connector sites of poly-ether-ketone-ketone (PEKK) frameworks.

Purpose. The purpose of this in vitro study was to investigate the effect of cantilever length and cross-sectional dimension of connectors on the fracture resistance of poly-ether-ketone-ketone (PEKK) frameworks.

Material and Methods. Sixty frameworks were digitally designed and milled from PEKK blanks. All specimens were prepared in 6 different groups (n=10); group 4.07 (3 mm width x 4 mm height and 7 mm cantilever), group 4.10 (3 mm width x 4 mm height and 10 mm cantilever), group 4.17 (3 mm width x 4 mm height and 17 mm cantilever), group 5.07 (3 mm width x 5 mm height x 7 mm cantilever), group 5.10 (3 mm width x 5 mm height and 10 mm cantilever), and group 5.17 (3mm width x 5 mm height and 17 mm cantilever). The specimens were subjected to a static load until catastrophic fracture occurred, directed by a sudden load drop indicating maximum load-to-fracture values. Statistical analysis was performed by using two-way analysis of variance (ANOVA) followed by the Sidak post hoc test (α=.05).

Results. The two-way ANOVA revealed that the interaction between connector cross-sectional area and cantilever length on load-to-fracture values was found statistically significant (P<.001). The post hoc Sidak test revealed that there were no statistically significant differences were found between Group 4.07 and Group 5.10 (P=.076).

Conclusion. Load-to-fracture values were significantly decreased by increased cantilever lengths and decreased connector sizes. The highest load-to-fracture value was 409.91 ± 3 N was found in Group 5.07. Groups with 17 mm cantilevers (Groups 4.17 and 5.17) could not significantly increase by an increase in connector size as much as small cantilever length groups (Groups 4.07, 5.07, and 4.10).

Clinical Implication: Connector size and cantilever lengths of PEKK dental fixed prostheses should be designed with caution.

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Contributors

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The statistical analysis was conducted in part by Dr. Elias Kontogiorgos. All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

PAEK	Poly-Aryl-Ether-Ketone
PEEK	Poly-Ether-Ether-Ketone
PEKK	Poly-Ether-Ketone-Ketone
CAD/CAM	Computer-aided design/computer assisted manufacture
Y-TZP	Yttria partially stabilized tetragonal zirconia

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1. INTRODUCTION

Polyaryletherketone (PAEK) is a family of high-performance thermoplastic polymer that has been used in the medical and industrial fields for many years, with polyetherketoneketone (PEKK) introduced as the first member in 1962.[1] PAEK is a linear aromatic polyether ketone represented by ultrahigh molecular weight polyethylene.[1] These high-performance polymers have been used in the automotive, aerospace, and even in the orthopedic industry.[2,3] PAEK polymers have even been successfully applied as bearing surfaces for total joint replacements and bone replacements for maxillo-facial and cranial implants.[3] PEKK stands at the apex of the PAEK family due to its high performing mechanical properties, compared with the other members including polyetheretherketone (PEEK).[4] PEEK and PEKK have gained favor in the dental community for various applications, such as healing caps, provisional abutments, and implant-supported fixed frameworks.[5,6] These methacrylate-free high-performance thermoplastic polymers become more favored than other dental materials such as titanium and zirconia due to their properties resembling that of cortical bone, having high strength and stiffness, and good resistance to hydrolysis.[3,4,7]

Due to its higher ratio of keto- and ether-groups, which increases polarity and backbone rigidity, PEKK has a higher glass transition and melting temperature compared with PEEK, thus contributing to why it stands at the apex of the PAEK family pyramid in terms of quality of thermoplastics.[8-12] PEKK's higher ratio of keto- groups increases the polymer's chains stiffness, providing better physical and mechanical properties, such as polish ability, flexure, tensile, and compressive strength compared to PEEK.[3] Pekkton ivory (Cendres+Métaux), a PEKK product, has up to 80% greater compression strength than PEEK.[13-15] PEKK is a viable biomaterial to be considered for implant fixed dental prostheses due to its mechanical properties, stability in high temperatures, chemical resistance, shock-absorbing capabilities, biocompatibility, manufacturing versatility, light weight and bonding compatibility to an assortment of veneering materials.[14,16-18] PEKK, optimized for dental application with fillers, displays a very opaque gray/bone-like color, therefore it is not suitable for esthetic restorations as a monolithic structure, as it would require additional esthetic veneering material.[16] Fokas et al[18] found that etching PEKK with sulfuric acid and air abrading with tribochemical silica-coating significantly increases the tensile bonding stability between PEKK and resin composite. However, compared with other dental materials, such as zirconia, lithium disilicate, and alloy frameworks, the tensile bond strength of resin composite with PEKK showed comparatively lower bond strength.[18]

PEEK and PEKK have even been found to be able to withstand gamma- and steam-sterilization without surface degradation.[19] Comparing PEEK with different composite resins and poly methyl methacrylates after aging the specimens in different storage media, PEEK showed the lowest solubility and water absorption values.[20] It was also found that when PEKK was used as an underlying substructure, it showed higher survival rates in fatigue limits (790.4 N), compared with zirconia (608.7 N) and metal composite veneered crowns (442.8 N).[21] This is likely due to PEKK's similar modulus of elasticity (5.1 Gpa) to light cured composite (4.5 Gpa) in comparison with zirconia (210 GPa) and metal (218 Gpa).[21,22] Ultimately, large mismatches between substructures and veneering material result in higher tensile stresses which could lead to crown failure.[23] When considering choosing a material for implant supported frameworks, a decrease of stress transferred to abutment teeth and implants have been found due to high-performance polymers having elasticity similar to that of bone.[8,14,21] However, recent studies found that when using a low-elastic modulus material, such as PEKK, for an implant supported fixed dental prosthesis, less stress is placed on the framework, because higher stress was transmitted to the implants and adjacent prosthetic structures which favored stress dissipation.[24] Implant supported frameworks with high elastic moduli demonstrated more favorable outcomes, compared with low elastic moduli frameworks.[25] PEKK used as an implant supported framework continues to be controversial and requires further clinical and laboratory research.

Another noteworthy feature of PEKK is that it does not require any post-treated unlike other dental materials due its slow rate of crystallization, which usually requires a considerable amount of time and cost.[4,26] In regard to antibacterial activity, PEKK showed less bacterial adhesion on its surface compared with PEEK; specifically 37% less Staphylococcus epidermis.[27] When assessing inflammatory potential, PEKK has been shown to have less inflammatory response compared with poly methyl methacrylate.[28] PEEK and PEKK also have been shown to be compatible for imaging techniques due to their radiolucency.[29]

Different manufacturing methods of PEKK are recommended for different applications in a variety of ways, including injection moulding with pellets, hot pressing with ingots, milling by using computer-aided design/computer assisted manufacture (CAD/CAM) with blanks, or three-dimensional (3D) manufacturing via additive manufacturing (AM).[13,21,30] CAD/CAM has changed the field of dentistry considerably.[31,32] With the increased use of CAD/CAM technology in dental practices, 3D manufacturing has also become more common. 3D manufacturing can be branched off into two categories: additive manufacturing (AM) and subtractive manufacturing (SM).[33,34] SM, more commonly known as milling, creates a desired form out of a homogenous ceramic block by means of cutting tools. PEKK is versatile in its processing methods as it can be milled or hot-pressed (Cendres+Métaux). For the pressing procedure, special furnaces are recommended to allow for cooling during actively pressing. However, Alsadon et al[35] provided hot pressing parameters for Pekkton ivory by using a standard pressing furnace without compromising mechanical and physical properties. Producing Pekkton by CAD/CAM milling are not subject to increased time requirements and technique sensitive issues that are seen during hot pressing with standard ceramic pressing furnaces.[35] Comparing the two manufacturing methods of PEKK, pressed PEKK samples showed no significant difference in mechanical and optical properties compared with CAD/CAM.[35]

Han et al[16] reported about PEKK as a framework material for implant-supported complete fixed dental prosthesis (ISCFDP) of a fully edentulous maxilla. One of the keys for long-term success of ISCFDP is the design and fabrication of the framework.[36-38] The most recurrent challenge found is the fracturing of the prosthesis infrastructure.[39] Many framework materials are available, including titanium, cobalt-chromium, zirconia, high performance polymers, and polymethyl methacrylate.[40] Prosthetic repairs of CAD/CAM milled titanium frameworks were found to be less than 1% compared with interim prosthesis made of acrylic resin, which were at 17%.[40] According to Tiossi et al, [22] milled titanium and zirconia frameworks both transferred similar strains to supporting maxilla when supported by 4 implants. The positioning and amount of implants supporting these frameworks also greatly affects the implant success as well as the prosthesis's stress bearing capacity.[41]

The size of the cantilever is also important when considering designing fixed dental prostheses. Distal cantilevers have been incorporated into the design in order to decrease the number of implants placed and limit the need for surgical intervention and have shown high implant and prosthetic survival rates.[42,43] Alshahrani et al[8] demonstrated that increased occlusocervical thickness and decreased cantilever length allowed zirconia frameworks to receive higher loads before failure. Full contour PEKK crowns have been shown to withstand a static fracture load of 1700 N.[21]

Critical areas dealing with minimum dimensions do not reside solely in the cantilevers, but also exist in the connector areas.[41] Connectors in fixed prosthodontics are the portion of a fixed partial denture that unites the retainer(s) and pontic(s).[44] Fractures most often occur around the connector areas between retainers and pontics.[45-47] Ogino et al[48] suggested a connector cross-sectional area of more than 5 mm^2 for zirconia fixed partial dentures.[48] Onodera et al[49] looked at cross-sectional areas of 5 mm^2, 7 mm^2, and 9 mm^2 for zirconia molar fixed partial dentures and found that 7 mm^2 can be used clinically for 3-unit fixed partial bridges in posterior mandible.[49]

When considering designs, critical factors such as cantilever length and cross-sectional dimension of connector sites are especially important in posterior sites due to higher masticatory forces exhibited in that area.[50-51] To the author's knowledge, no studies have evaluated the cantilever optimum thickness and cantilever length for PEKK as an implant-supported complete fixed dental prosthesis. The purpose of this in vitro study was to investigate the effect of cantilever length and cross-sectional dimension of connector sites on the load-to-fracture of PEKK frameworks. The null hypothesis is that there will be no statistically significant differences in load-to-fracture values among different cantilever lengths and cross-sectional dimensions of cantilevered PEKK prostheses.

2. MATERIALS AND METHODS

2.1 Milled specimen

Sixty cantilevered fixed dental prostheses were digitally designed and fabricated for testing by CAD software (Exocad; Exocad America Inc). All specimens were prepared in 6 different groups (n=10) of two different connector sizes (3 mm width x 4 mm height and 3 mm width x 5 mm height) and three different cantilever distances (7 mm (representing the premolar), 10 mm (representing the molar), and 17 mm (representing the premolar and molar together) (Table 1).[52] The frameworks were milled from PEKK blanks (Pekkton Ivory Millable Disc; Cendres+Metaux) with a computer-aided milling machine (Milling Unit M1 Heavy; Zirkonzahn Inc).

Group Name	Connector Area	Cantilever Length
Group 4.07	3 mm x 4 mm	7 mm
Group 4.10	3 mm x 4 mm	10 mm
Group 4.17	3 mm x 4 mm	17 mm
Group 5.07	3 mm x 5 mm	7 mm
Group 5.10	3 mm x 5 mm	10 mm
Group 5.17	3 mm x 5 mm	17 mm

Table 1. Specimen group name and associated connector area and cantilever length dimensions

2.2 Preparation of samples for load-to-fracture test

Specimens were visually inspected with magnifying loops (Heine HR; Heine USA LTD) ensure the absence of defects or irregularities were present. Frameworks sprues from discs were cut with handpiece and E-cutter carbide bur (H79E.11.040 HP; Brasseler USA). Digital calipers (Digital Caliper 01407A; Neiko) were used to measure each specimens' cantilever length and connector size to ensure correct sizes to ± 0.05 mm.

2.3 Load-to-fracture test

Each specimen was attached by using a clasp attached to the first 20 mm of each framework (Fig. 1). The load frame was placed to contact the framework halfway through the last tooth of the free end and then loaded in the testing machine (Fig. 2). The loading was applied using a round stainless-steel ball on a load cell with a radius of 6 mm (Fig. 2) (Ball End Hex Key; Tekton).[53] The machine was calibrated with a load cell of 30 kN and set to a crosshead speed was set at 1 mm/min loaded in a vertical direction. The PEKK frameworks was subjected to a static load that was applied in a vertical direction by using a biaxial servo hydraulic load frame and universal testing machine (5567 Universal Testing Machine; Instron Ltd). All specimens were loaded from 0 Newtons (N) until catastrophic fracture occurred, directed by a sudden load drop indicating maximum load-to-fracture values. Corresponding values were recorded and statistically analyzed by using a software program (Bluehill v1.5; Instron Ltd).

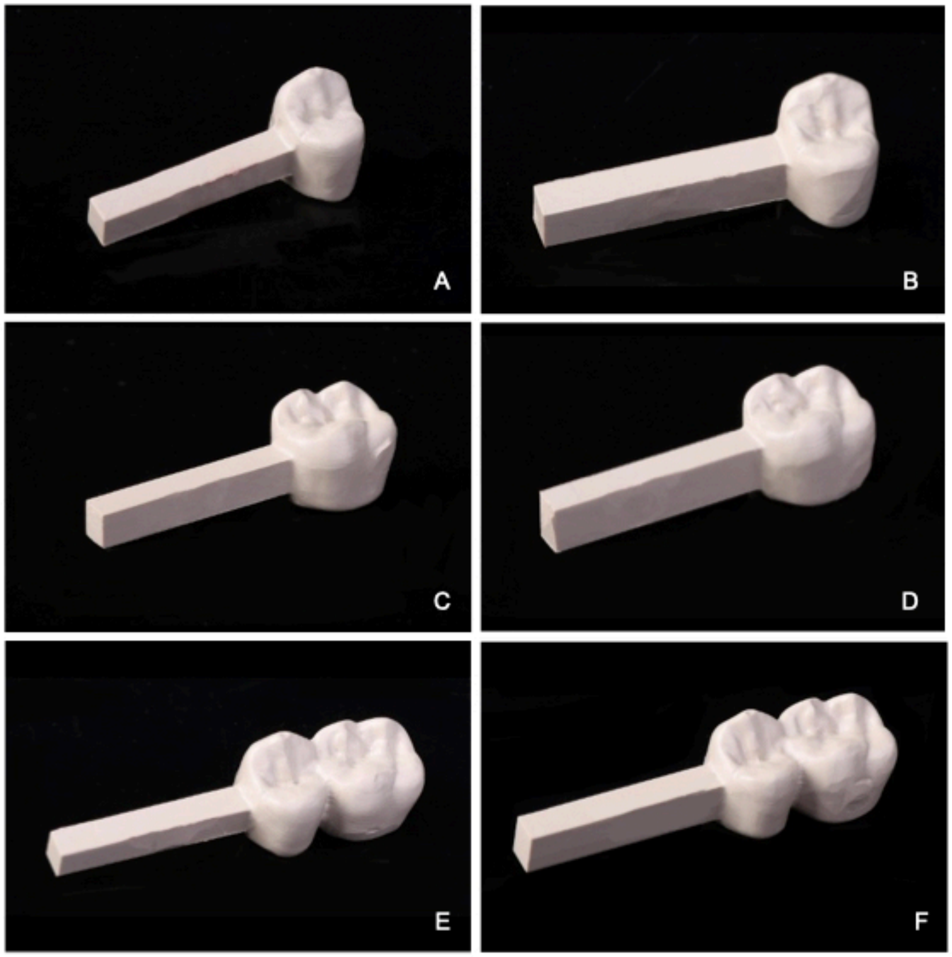

Figure 1. Specimens. A, Group 4.07. B, Group 5.07. C, Group 4.10. D, Group 5.10. E, Group 4.17. F, Group 5.17.

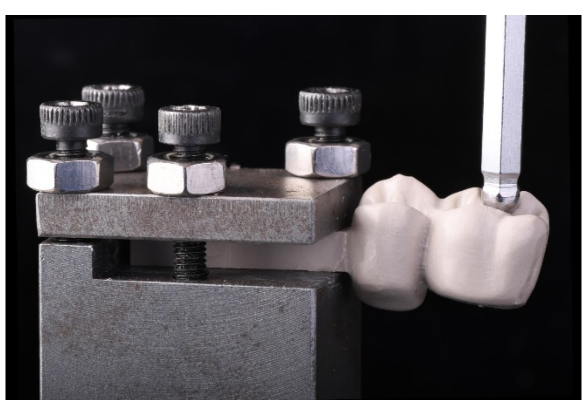

Figure 2. Load frame test set up with Group 4.17

2.4 Calculations and statistical analysis

The data measurements collected from each specimen were reported in Newtons (N). Data was analyzed by using a statistical software program (IBM SPSS Statistics, v25.0; IBM Corp). A statistical analysis was carried out to evaluate the influence of cantilever length and cross-sectional area on force-to-fracture by a two-way analysis of variance (ANOVA) test. To investigate the interaction between connector cross-sectional area and cantilever length on load-to-fracture values, a Sidak post-hoc test was used for multiple comparison correction. The statistical calculations were done using a software SPSS 23 (SPSS Incl) at $\alpha = .05$.

3. RESULTS

Table 2 shows the means ± standard deviation values of load-to-fracture values; 209.47 ± 15.83 N for Group 4.07, 409.91 ± 37.99 N for Group 5.07; 124.12 ± 6.09 N for Group 4.10; 232.35 ± 4.88 N for Group 5.10; 71.83 ± 8.85 N for Group 4.17, 98.33 ± 4.78 N for Group 5.17. The load exhibited by the specimens ranged between 409.91 N (Group 5.07) and 71.83 N (Group 4.17).

Group	4.07	5.07	4.10	5.10	4.17	5.17
Cantilever (mm)	7		10		17	
Connector Height (mm)	4	5	4	5	4	5
Mean (N)	209.47	409.91	124.12	232.35	71.83	98.33
Standard Deviation (N)	15.83	37.99	6.09	4.88	8.85	4.78
Minimum (N)	186.0	356.4	117.6	224.8	55.6	90.8
Maximum (N)	227.4	486.3	136.8	239.5	84.4	107.1

Table 2. Descriptive statistics for load-to-fracture (N) for 6 groups (4.07, 5.07, 4.10, 5.10, 4.17, 5.17)

The two-way ANOVA test revealed that there was a statistically significant difference as a function of cantilever, connector size, and both factors ($P \leq .001$).

Effect	**Num *df***	**F**	***P***
Cantilever	2	823.2	≤.001
Connector Size	1	605.1	≤.001
Cantilever*Connector Size	2	122.4	≤.001

Table 3. Sidak Post Hoc Test Results two-way ANOVA test

The post hoc Sidak test revealed that there was a statistically significant difference among the Groups 5.07, 4.10, 5.10, 4.17 and 5.17 ($P \leq .001$), while there were no statistically significant differences found between Group 4.07 and Group 5.10 (P=.076) (Table 4). Group 5.07, with a shorter cantilever length and increased connector cross-sectional dimension, demonstrated the highest values of load-to-fracture.

Group Comparisons		Significance
4.07	5.07	$P \leq .001$
4.07	4.10	$P \leq .001$
4.07	5.10	$P = .076$
4.07	4.17	$P \leq .001$
4.07	5.17	$P \leq .001$
5.07	4.10	$P \leq .001$
5.07	5.10	$P \leq .001$
5.07	4.17	$P \leq .001$
5.07	5.17	$P \leq .001$
4.10	5.10	$P \leq .001$
4.10	4.17	$P \leq .001$
4.10	5.17	$P = .027$
5.10	4.17	$P \leq .001$
5.10	5.17	$P \leq .001$
4.17	5.17	$P = .021$

Table 4. Multiple comparisons results by post hoc Sidak test

Figure 3 shows the load-to-fracture values were significantly decreased by increased cantilever lengths and decreased connector sizes. The lowest value was found in the Group 4.17, which had the smallest connector size area and the longest cantilever length.

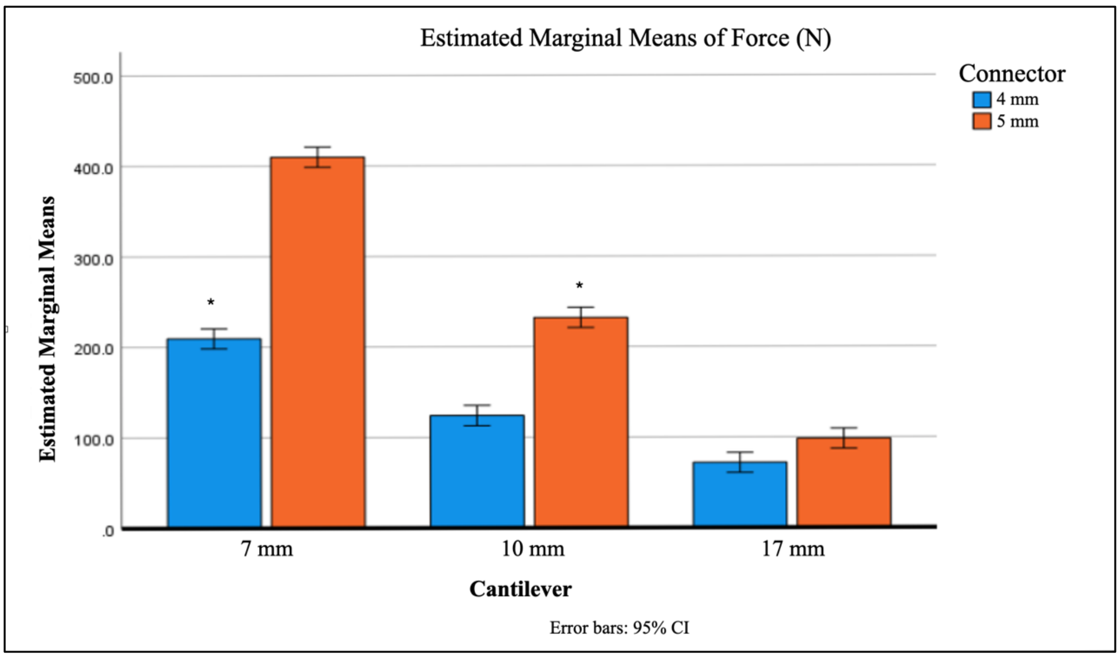

Figure 3. Bar graph of mean values of load-to-fracture (N).
Note. * indicates no significant difference between groups.

4. DISCUSSION

This in vitro study investigated the effect of different cantilever lengths and cross-sectional dimensions of connector site on the load-to-fracture of PEKK fixed dental prostheses. Group 5.07, with a shorter cantilever length and increased connector cross-sectional dimension, demonstrated the highest values of load-to-fracture. The lowest value was found in the Group 4.17, which had the smallest connector size area and the longest cantilever length. Among all groups, there were no statistically significant differences of load-to-fracture values only between Group 5.10 and Group 4.07 (P=.076). The null hypotheses stating that there will be no statistically significant differences in load-to-fracture values among different cantilever lengths and different cross-sectional dimensions of cantilevered PEKK prostheses was rejected.

Frameworks with free standing segments where only one end is supported, otherwise known as cantilevers, have areas of high stress at or distal to their posterior abutments.[54] This can lead to scenarios of problems including abutment screw fracture, gold alloy retaining screw fracture and framework fracture.[55] The present study confirmed with Zarb and Schmitt's research which suggested to increase connector size with an increase of cantilever length.[55] Glanz stated that the greater the force generated on a framework with increased cantilever lengths, frameworks would be more likely to undergo deformation compared with frameworks with decreased cantilever undergoing lesser forces.[56] The present study showed similar trends as increased cantilever lengths resulted in lower fracture resistance. Alshahrani et al[8] evaluated load-to-fracture of monolithic zirconia cantilevered frameworks and found that increased occluso-cervical thickness and decreased cantilever length withstood higher loads. However, Yilmaz et al[57] performed load-to-failure testing on high performance polymers, including PEKK with and without titanium bases, demonstrating that load-to-failures of 10 mm cantilever PEKK without titanium bases at higher values (33 MPa) compared with the present study (10 - 15 MPa).[57]

Chong et al[52] evaluated cross-sectional dimension of connector sites and variations in cantilever lengths on zirconia implant frameworks. They revealed similar trends to the present study in that cross-sectional area connector dimensions of 3 x 5 mm failed at higher fracture loads than specimens with 3 x 4 mm connector dimensions. They also similarly found that frameworks with 7 mm cantilever length fractured at higher failure loads compared to10 mm cantilevers. The present study showed similar trends. However, when evaluating the load-to-fracture means slope of 3 x 4 mm connector areas transitioning from 7 mm cantilevers to 10 mm cantilevers, this study had a slope of -28, compared to Chong et al. -75 (Figure 4).[52] Therefore, PEKK compared with zirconia showed a more gradual slope with 3 x 4 mm connector areas increasing cantilevers from 7 mm to 10 mm. Conversely, when evaluating the load-to-fracture means slope of 3 x 5 mm connector areas (1mm increase in connector area height) transitioning from 7 mm cantilevers to 10 mm cantilevers, the present study had a slope of -59, compared with the data (-29) of other studies.[52] Therefore, PEKK framework demonstrated a steeper slope with a 1 mm increase in connector height transitioning from 7 mm to 10 mm cantilevers than zirconia framework.

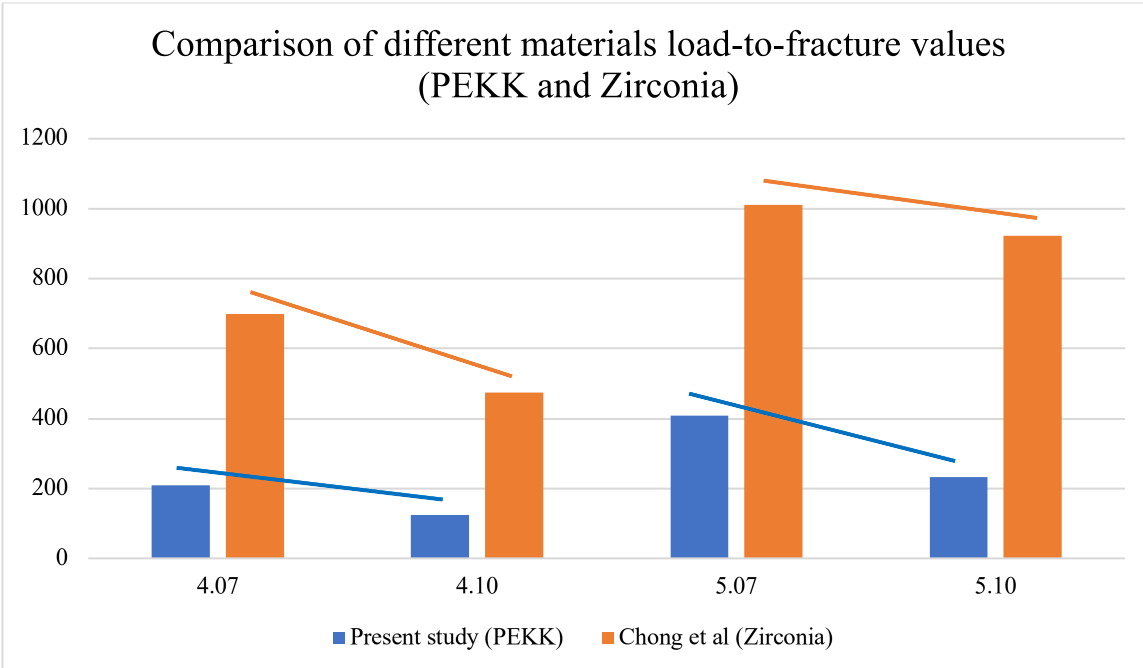

Figure 4. Graph indicating trend of strength change by different cantilever lengths and connector sizes of two different materials: zirconia (Chong et al) and PEKK (present study)

When considering framework designs, geometry and features of the prosthesis material need to be considered.[58] Minimum requirements of 3 mm of thickness have been reported for cast alloy frameworks to provide adequate rigidity.[59] In the present study, connector surface areas of 3 x 4 mm (12 mm^2) and 3 x 5 mm (15 mm^2). Conversely, Chong et al[52] found that the cross-sectional area of the connector dimension and the cantilever length had no statistically significant interaction between them, thus increasing the cantilever length showed no statistically significant interaction between the cross-sectional connector area dimension and cantilever length. Pantea et al[50] found that not only does the surface area of connectors have an important impact on load distribution of 3-unit zirconia infrastructures, but an elliptical connector shape also revealed higher flexural strength over a circular connector shape.

The present study found no statistically significant differences were found between the Group 5.10 and Group 4.07 (*P*=.076). This finding can be translated in a clinical situation. When deciding between a 7 mm (mesiodistal width average of a premolar) and 10 mm (mesiodistal width average of a molar) cantilever in a PEKK framework, considering an increase in the height of the connector by 1 mm for 10 mm cantilever will have a similar load-to-fracture strength with a 7 mm cantilever. It means the load-to-fracture strength can be improved by 1 mm increase of connector height when 10 mm cantilever is clinically required due to chewing efficiency and opposing arch contacts.

Limitations of the present study were the use of a traditional load-to-failure test, which uses a static load applied in a vertical direction loading the specimens until catastrophic fracture occurred, directed by a sudden load drop indicating maximum load-to-fracture value. Although load-to-fracture testing does not fully reflect the clinical situation, it may be useful for initial in-vitro testing to assess the fracture force of PEKK.[8] Another limitation of the present study was that no ageing, in terms of mechanical loading or thermocycling, were performed. In order to better simulate intra-oral environments and conditions, specimens should be thermocycled and undergo cyclic loading. Connector shape designs are typically oval in shape compared to this study which utilized a rectangular shape in order to be held by the testing framework. Restorations in the area of the molars should be able to sustain an occlusal load of around 500 N.[60] Gibbs et al reported 462N mean maximum clenching force in adults with tooth loss in comparison with 720 N in adults with teeth.[61] Comparing these requirements with the present study's findings, the highest mean fracture resistance value (486 N) was found in Group 5.07, which is lower than occlusal load and clenching force reported.[61] Future studies should also incorporate clinical performance test to observe how PEKK performs when other intra-oral factors are involved.

5. CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn:

1. Load-to-fracture values were significantly decreased by increased cantilever lengths and decreased connector sizes.
2. The highest load-to-fracture value of cantilevered PEKK fixed dental prostheses was 409.91 ± 38 N in Group 5.07, while the lowest was 55.6 ± 8.85 N in Group 4.17.
3. Load-to-fracture values at the groups of 17 mm cantilever (Group 4.17 and 5.17) could not significantly increase by an increase in connector size as much as small cantilever length groups (Group 4.07, 5.07, and 4.10).

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