Evaluation of two-body wear rate and roughness of polyetheretherketone and zirconia opposing enamel structure: an in-vitro study

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Background/aim
Investigation of polyetheretherketone (PEEK), a new synthetic thermoplastic polymer, as an alternative for zirconia for veneering frameworks, to be used with weakened abutment teeth, as in cases of patients with parafunctional habits. This study aimed to investigate the two-body wear rate and roughness of PEEK and zirconia by itself and against human enamel.

Materials and methods
A total of six disc-shaped zirconia (n=6) and six disc-shaped PEEK specimens (n=6) (10 mm in diameter with a thickness of 2 mm) were prepared. Human enamel antagonists were produced by sectioning of 12 premolars. The two-body wear testing was performed using chewing simulator. Weight loss was assessed by electronic analytical balance. The optical profilometry was used for roughness evaluation.

Results
The findings of this study revealed that PEEK showed a comparable effect upon comparison with zirconia, although there was a statistically nonsignificant difference between weight changes recorded for wear in both PEEK and zirconia groups, tested alone or with enamel antagonists, as indicated by the unpaired t test. Moreover, the optical profilometer revealed that, the difference between surface roughness changes recorded for both groups, tested alone or with enamel antagonists, was statistically nonsignificant as indicated by the unpaired t test.

Conclusion
PEEK showed a promising effect in terms of antagonistic tooth wear and roughness upon comparison with zirconia. However, the results were not significant between both materials.

Keywords:
chewing simulator, enamel antagonists, polyetheretherketone, roughness, zirconia

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Introduction

In dentistry, optical and strength properties are vital. Zirconia restorations have the highest mechanical properties and are also visually pleasing, when compared with ceramometallic restorations due to their good esthetics; although their optical characteristics change with different systems, their former characteristics courtesy the zirconia use over porcelain fused to metal restorations [1,2].

Wear and roughness of the dental enamel is becoming an effective issue for long serviceability. A study of the mechanisms and effective factors in tooth wear and roughness is, consequently, searchingly significant. Weight loss is measured by an electronic analytical balance [3]. The wear rate of tooth enamel should equal that of ceramic restorations, which is around 40 μm/year. It has been believed that ceramic use produces abrasion in case of great occlusal load; nonetheless, it was less profound due to the crystalline microstructure. Zirconia has high abrasive resistance; however, its characteristics differ definitively from zirconia, with porcelain veneer resulting in dissimilar wear performance [4].

In contrast, polymers have low modulus of elasticity, which permits functional stress absorption through deformation. The added advantage is the low hardness compared with the enamel antagonists [5].

The real emergent concern in esthetic polymers can be furthermore correlated to technology advances, quicker manipulation, and fewer expenses, in addition to enhanced mechanical properties, besides the benefit of applying in thinner thickness compared with ceramic materials [6].

Polyetheretherketone (PEEK) is an innovative polymer in this era of dental investigation. PEEK is a subgroup from polyaryletherketone main group. The mode of presentation of PEEK is either pressed blanks (CAD/CAM millied), prepressed pellets, or granular mode.

Owing to the outstanding properties, PEEK has been extensively used in medical and dental fields, and is recommended to be a promising material in fixed prosthodontics field [7].

An earlier study explained the fabrication of three single crowns for a patient who was looking for an esthetic metal-free crowns, and all-ceramic restorations were not recommended, because of the possibility for abrasion of the opposing teeth and force transmission to the weak abutment teeth. The most recommended restoration was a PEEK framework with an indirect light-cured composite resin veneer. This selection allowed characteristics such as biological compatibility, opposing teeth protection, an absorption effect, hardness almost equal to that of dentin, easy repair in case of chipping, and high comfort. The use of veneered PEEK frameworks could be a good alternative for weakened abutment teeth in cases of patients with parafunctional habits [8].

The aim of this study was to assess the two-body wear rate and roughness of PEEK and zirconia by itself and against human enamel.

Materials and methods

Materials

Two types of materials were used in this study to fabricate 12 disc-shaped specimens.

Six discs were fabricated from; granular PEEK BioHPP thermoplastic [BioHPP (granulate) 20 g; Bredent, Senden, Germany], and the other six discs were fabricated from Ultra-translucent multilayered zirconia blocks (KATANATM; UTML A2, Miyoshi-cho, Japan).

Study design

Experimental groups

The present study included 12 samples divided into two groups of six specimens each (*n*=6). The first group contained PEEK samples, and the second group included zirconia samples.

Enamel antagonist groups

Six premolars were extracted recently for orthodontic demands from the outpatient clinic of the National Research Centre, Cairo, Egypt. Teeth with worn-out cusps or too sharp or fractured teeth were excluded. The premolars were used in this study for in-vitro wear testing against the experimental materials.

Ethical approval

The research was approved by the Ethical Committee of the National Research Centre with registration no. 18184.

Polyetheretherketone sample construction

Wax patterns of six discs (10 mm in diameter with a thickness of 2 mm) were constructed and sprues were attached. The assembly was attached to the investment ring then invested using special investment material Brevest for 2 presses (Bredent, Senden, Germany). After material setting, the mold was then heated to 630°C; thereafter, the temperature was gradually increased by a rate of 8°C/min until it reached 850°C in a preheated oven (IBEX Dental Oven, Richardson, Texas, USA) for wax burnout for 60 min before starting the melting process. Granular PEEK material was placed in the melting channel. Thereafter, the ring was placed back into the preheated oven for 20 min at a temperature of 400°C to get a creamy molten material with uniform appearance, indicating that the material was ready for pressing and injection pressure of seven bars. By the end of the process, the mold was allowed to cool for 35 min. The mold was then placed in water bath for 10 min; thereafter, devesting was carried out first with scissors to remove the mold followed by using a pneumatic devesting chisel. The fine blasting device was used to get finished and polished discs.

Zirconia sample construction

A total of six disc-shaped specimens (10 mm in diameter with thickness of 2 mm) were prepared from zirconia blocks. The discs were fabricated using CAD CAM (Sirona inlab 16 software; Cadcam, Bensheim Germany) and were milled using a dry milling machine (Sirona Mcx5 Milling machine, Bensheim Germany). All specimens were sintered according to the manufacturer's directions with a sintering machine (Sirona infire HTC furnace, Bensheim Germany).

Human enamel antagonist specimen preparation

Human enamel used in this study for in-vitro wear testing against the experimental materials was produced by sectioning the six premolars that were recently extracted. Longitudinal sectioning was performed mesiodistally using a low-speed cutting

Figure 1

Chewing simulator used for wear simulation test (ROBOTA Co.).

machine (Low Speed Saw 11e1180; Isomet, Manassas, VA, USA) into two equal buccal and lingual halves. The enamel antagonist specimens were firmly gripped by tightening the Jacob's chuck of the upper part of the wear simulator [3].

Wear simulation

The two-body wear testing was performed using a programmable logic-controlled equipment (four-station multimodal ROBOTA chewing simulator; ROBOTA Co., Giza, Cairo, Egypt) (Fig. 1), integrated with thermocyclic protocol operated on servomotor (Model ACH-09075DC-T; AD-Tech Technology Co. Ltd, Frankfurt, Germany). The chewing simulator has four chambers simulating the vertical and horizontal movements simultaneously in the thermodynamic condition. Each of the chambers consists of an upper Jacob's chuck as a tooth antagonist holder that can be tightened with a screw (Fig. 2a) and a lower plastic sample holder specially designed with a circular depression having the same dimensions of the specimen to be tested. The plastic holder is fixed in the lower chamber that contains distilled water to be used during testing procedures (Fig. 2b).

Both groups' samples (PEEK and zirconia and their corresponding teeth specimens) were mounted and tested sequentially under 50 N load for a number of 37 500 cycles under the wear testing parameters mentioned in Table 1. This wear protocol was chosen to simulate 3 months clinically according to previous studies [9].

Wear evaluated through weight loss and roughness changes

Weight loss measurement

Weight loss was measured by an electronic analytical balance (Sartorius; Biopharmaceutical and Laboratories, Goettingen, Germany), as shown in Fig. 2c, with an accuracy of 0.0001 g in calculating the difference in weight before and after each wear cycle. As this electronic balance had a fully automated calibration technology and a microweighing scale, values of all the mounted discs and antagonist samples were accurately measured. Each mounted sample was cleaned and dried with tissue paper before weighing. To ensure accuracy, the balance was kept on a free-standing table at all times – away from vibrations – and the specimens were weighed with the glass doors of the balance closed to avoid the effect of air drafts.

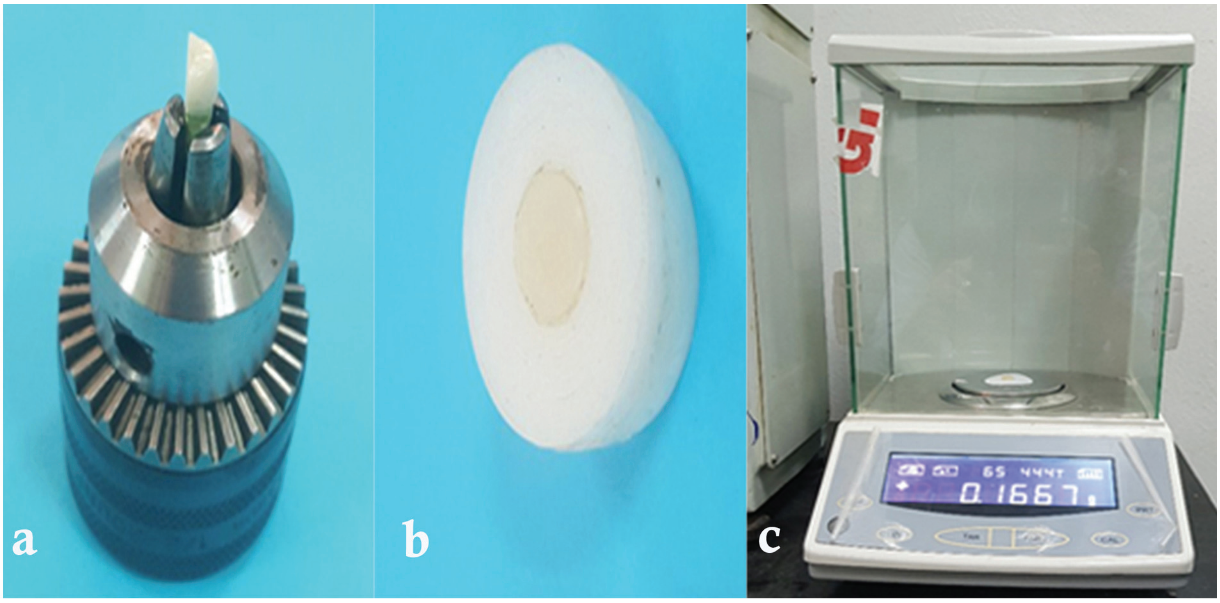
Roughness evaluation

Roughness change measurement

The optical profilometry tends to fulfill the need for quantitative characterization of surface topography without contact [10].

Quantitative analysis of two-body wear on specimens and their antagonists was carried out before and after

Figure 2



(a) Tooth section mounted and tightened into Jackob's chuck in the upper compartment as antagonist. (b) Material disc mounted in the plastic holder of the lower compartment. (c) Electronic analytical balance for weight measurement.

Table 1 Wear simulation testing parameters

Vertical movement	1 mm
Horizontal movement	3 mm
Rising speed	60 mm/s
Descending speed	40 mm/s
Forward speed	60 mm/s
Backward speed	40 mm/s
Cycle frequency	1.6 Hz (96 cycle/min)
Time of 50 000 cycles	6.51 h
Weight per specimen	50 N

loading in a three-dimensional (3D)-surface analyzer system. Specimens were photographed using USB digital microscope with a built-in camera (Scope Capture Digital Microscope, Guangdong, China) connected to an IBM-compatible personal computer using a fixed magnification of ×120. The images were recorded with a resolution of 1280×1024 pixel per image. Digital microscope images were cropped to 350×400 pixels using Microsoft office picture manager to specify/standardize the area of roughness measurement. This area was chosen on the basis of the dimension of the typical bacteria expected to adhere to the composite surface *in vivo* [11].

The cropped images were analyzed using WSxM software (Ver 5 develop 4.1; Nanotec, Electronica SL, San Diego, California USA) [12].

Within the WSxM software, all limits, sizes, frames and measured parameters are expressed in pixels. Therefore, system calibration was performed to convert the pixels into absolute real-world units. Calibration was made by comparing an object of known size (a ruler in this study) with a scale generated by the software. WSxM software was used to calculate the average of heights (Ra) expressed in μm, which can be assumed as a reliable index of surface roughness [13].

To achieve a better reflection on the surface of the samples and to carry out a qualitative analysis of the wear areas, samples were examined and photographed using the same USB digital microscope at a fixed magnification of ×25. Subsequently, a 3D image of the surface profile of the specimens was created using a digital image analysis system (Image J 1.43U, National Institute of Health, USA). The unworn surface served as a reference. With this method, a 3D geometry of the worn surface was generated.

Statistical analysis

Data were presented as mean and SD for values. The results were analyzed using Graph Pad Instat (Graph Pad Inc., San Diego, California USA) software for windows. A value of *P* value less than or equal to 0.05 was considered statistically significant. After homogeneity of variance and normal distribution of errors had been confirmed, unpaired *t* test was carried out for comparison of both groups, while the paired t test was carried out for comparing before and after the wear test. The sample size (*n*=6) was large enough to detect large effect sizes for main effects and pair-wise comparisons, with the satisfactory level of power set at 80% and a 95% confidence interval.

Table 2 The mean values±SD for weight results for polyetheretherketone and zirconia before and after 3 months' wear simulation cycles

Variables	Samples			Paired *t* test	
	Before	After	Change	*t* value	*P* value
PEEK	0.178817±0.004	0.178133±0.0042	−0.00068±0.00022	5.8	0.002*
Zirconia	0.149875±0.003	0.1492±0.0026	−0.00068±0.00017	7.5	0.0007*
Unpaired *t* test	*t* value			0.0565	
	P value			0.9560 NS	

PEEK, polyetheretherketone. *Signifiant ($P<0.05$). Nonsignificant (NS) ($P>0.05$).

Table 3 The mean values±SD for weight results for both materials' antagonistic enamel cusp before and after 3 months' wear simulation cycles

Variables	Antagonist			Paired *t* test	
	Before	After	Change	*t* value	*P* value
PEEK enamel antagonist	0.663308±0.061	0.661958±0.062	−0.00135±0.0006	4.1	0.0155*
Zirconia enamel antagonist	0.679517±0.045	0.678733±0.044	−0.00078±0.0001	13.7	0.0002*
Unpaired *t* test	*t* value			1.88	
	P value			0.0881 NS	

PEEK, polyetheretherketone. Signifiant ($P<0.05$). Nonsignificant (NS) ($P>0.05$).

Results

Wear results by weight changes

The mean values and SD for weight measured in grams recorded on all materials before and after 3 months' wear simulation cycles are summarized in Tables 2 and 3. Weight recorded for the antagonistic enamel cusp is also shown.

In experimental groups

For the PEEK group, it was found that the weight mean value before wear was 0.178817±0.004 g, while after wear simulation, the mean value was 0.178133 ±0.0042 g, with a weight change mean value of −0.00068±0.00022 g, as shown in Table 2. The change was significant in weight, as validated by the paired *t* test (P=0.002<0.05).

For the zirconia group, it was shown that the weight mean value before wear was 0.149875±0.003 g, while after wear simulation, the mean value was 0.1492 ±0.0026 g, with a weight change mean value of −0.00068±0.00017 g, as shown in Table 2. The change in weight was significant, as confirmed by the paired *t* test (P=0.0007<0.05). The difference between weight changes recorded for both groups was statistically nonsignificant, as indicated by the unpaired *t* test (P=0.9560>0.05).

In enamel antagonist groups

For PEEK enamel antagonist group; it was found that the weight mean value before wear was 0.663308 ±0.061 g while after wear simulation the mean value was 0.661958±0.062 g, with a weight change mean value of −0.00135±0.0006 g, as shown in Table 3. The change in weight was significant, as validated by the paired *t* test (P=0.0155<0.05).

For the zirconia enamel antagonist group, it was found that the weight mean value before wear was 0.679517±0.045 g, while after wear simulation, the mean value was 0.678733±0.044 g, with a weight change mean value of −0.00078±0.0001 g, as shown in Table 3. The change in weight was significant, as confirmed by the paired *t* test (P=0.0002, $P<0.05$). The difference between weight changes recorded for both groups was statistically nonsignificant, as indicated by the unpaired *t* test (P=0.0881>0.05).

Roughness changes

The mean values and SD for surface roughness measured by average heights (μm) recorded on all materials' groups before and after 3 months' wear simulation cycles are summarized in Tables 4 and 5. Roughness recorded for the antagonistic enamel cusp is also shown.

In experimental groups

For the PEEK group, it was found that the surface roughness mean value before wear was 0.255317 ±0.0007 μm, while after wear simulation, the mean value was 0.254967±0.0013 μm, with a surface roughness change mean value of −0.00035 ±0.00078 μm, as shown in Table 4. The change in surface roughness was nonsignificant, as proved by paired *t* test (P=0.5886>0.05). Representative 3D

Table 4 The mean values±SD for surface roughness results for polyetheretherketone and zirconia before and after 3 months' wear simulation cycles

Variables	Samples			Paired *t* test	
	Before	After	Change	*t* value	*P* value
PEEK	0.255317±0.0007	0.254967±0.0013	−0.00035±0.00078	0.747	0.4886 NS
Zirconia	0.254167±0.0009	0.253817±0.001	−0.00035±0.00125	0.558	0.6006 NS
Unpaired *t* test	*t* value			0	
	P value			1 NS	

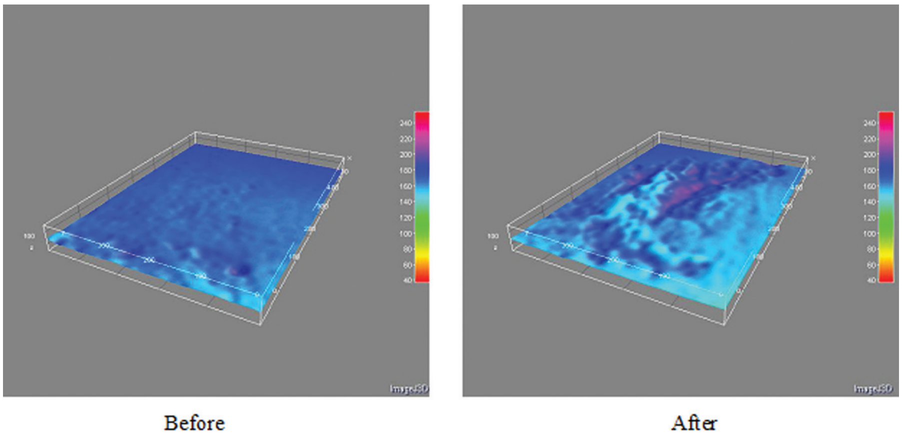
PEEK, polyetheretherketone. Signifiant ($P<0.05$). Nonsignificant (NS) ($P>0.05$).

Table 5 The mean values±SD for surface roughness results for both materials' antagonistic enamel cusp before and after 3 months' wear simulation cycles

Variables	Antagonist			Paired *t* test	
	Before	After	Change	*t* value	*P* value
PEEK enamel antagonist	0.255625±0.0023	0.256758±0.0015	0.001133±0.0029	0.691	0.5202 NS
Zirconia enamel antagonist	0.254842±0.002	0.258383±0.0019	0.00354±0.00384	1.7	0.1477 NS
Unpaired *t* test	*t* value			0.912	
	P value			0.3832 NS	

PEEK, polyetheretherketone. Signifiant ($P<0.05$). Nonsignificant (NS) ($P>0.05$).

Figure 3



Representative three-dimensional image showing surface topographic features for PEEK sample before and after 3 months' wear simulation cycles. PEEK, polyetheretherketone.

image showing surface topographic features for PEEK sample before and after 3 months wear simulation cycles is shown in Figs 3 and 4.

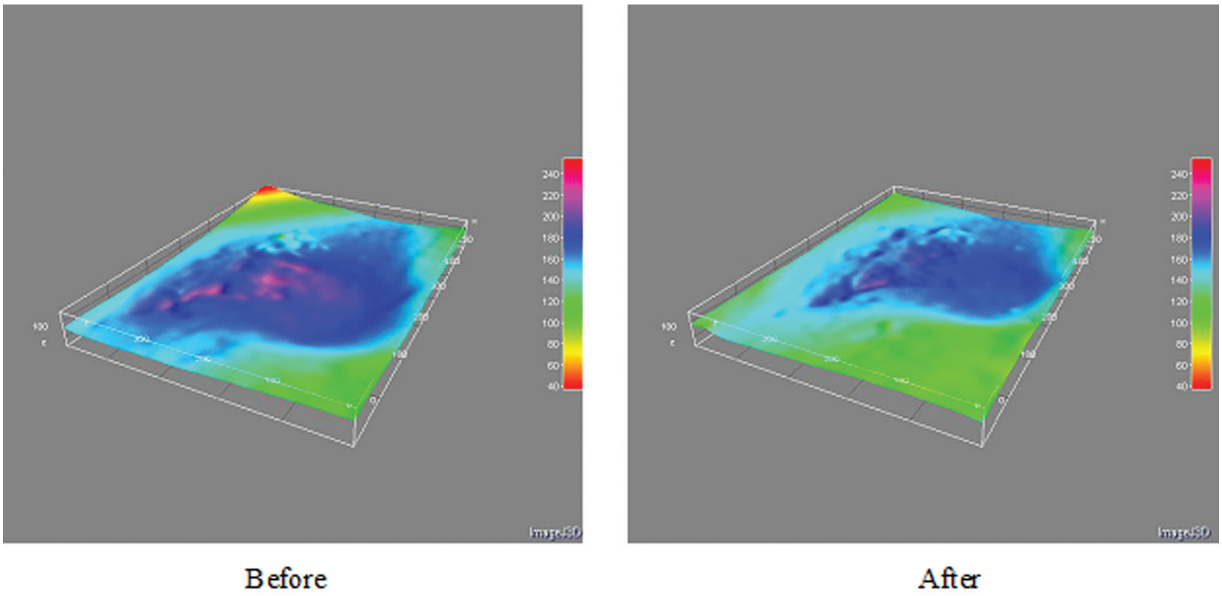
For the zirconia group, it was found that the surface roughness mean value before wear was 0.254167 ±0.0009 μm, while after wear simulation, the mean value was 0.253817±0.001 μm, with a surface roughness change mean value of −0.00035 ±0.00125 μm, as shown in Table 4. The change in surface roughness was nonsignificant, as proven by the paired *t* test (P=0.6006>0.05). Representative 3D image showing surface topographic features for zirconia sample before and after 3 months' wear simulation cycles is shown in Fig. 5.

The difference between surface roughness changes recorded for both groups was statistically nonsignificant, as indicated by the unpaired *t* test (P=1>0.05).

In enamel antagonist groups

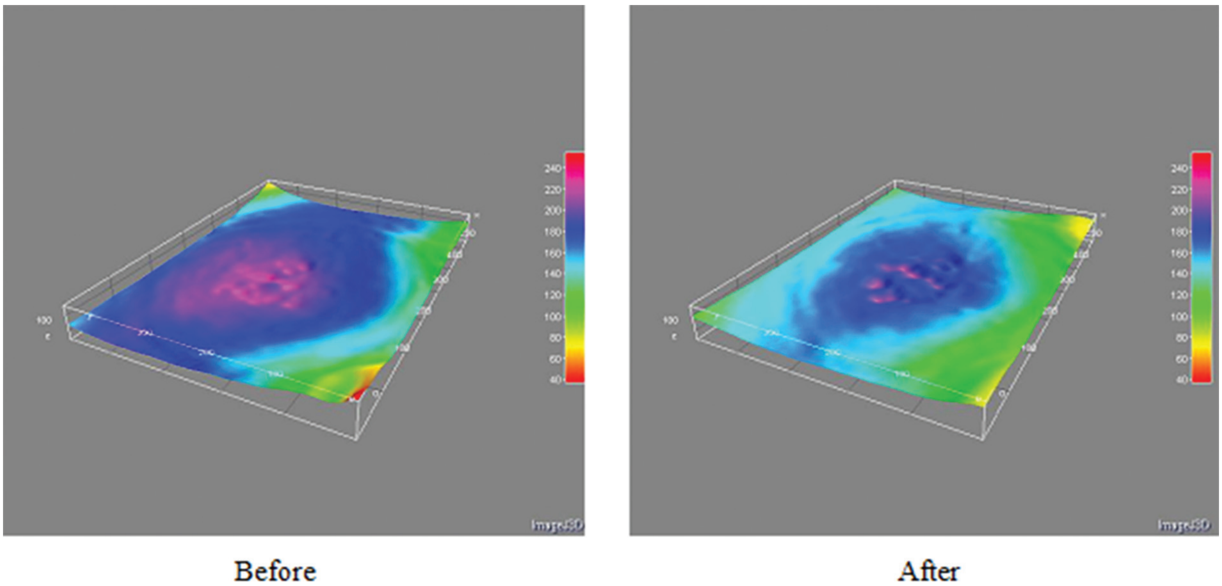
For the PEEK enamel antagonist group, it was found that the surface roughness mean value before wear was 0.255625±0.0023 μm, while after wear simulation, the mean value was 0.256758±0.0015 μm, with a surface roughness change mean value of 0.001133±0.0029 μm, as shown in Table 5. The change in surface roughness was nonsignificant, as indicated by the paired *t* test (P=0.5202> 0.05). Representative 3D image showing surface topographic features for PEEK antagonistic

Figure 4



Representative three-dimensional image showing surface topographic features for PEEK antagonistic enamel cusp before and after 3 months' wear simulation cycles. PEEK, polyetheretherketone.

Figure 5



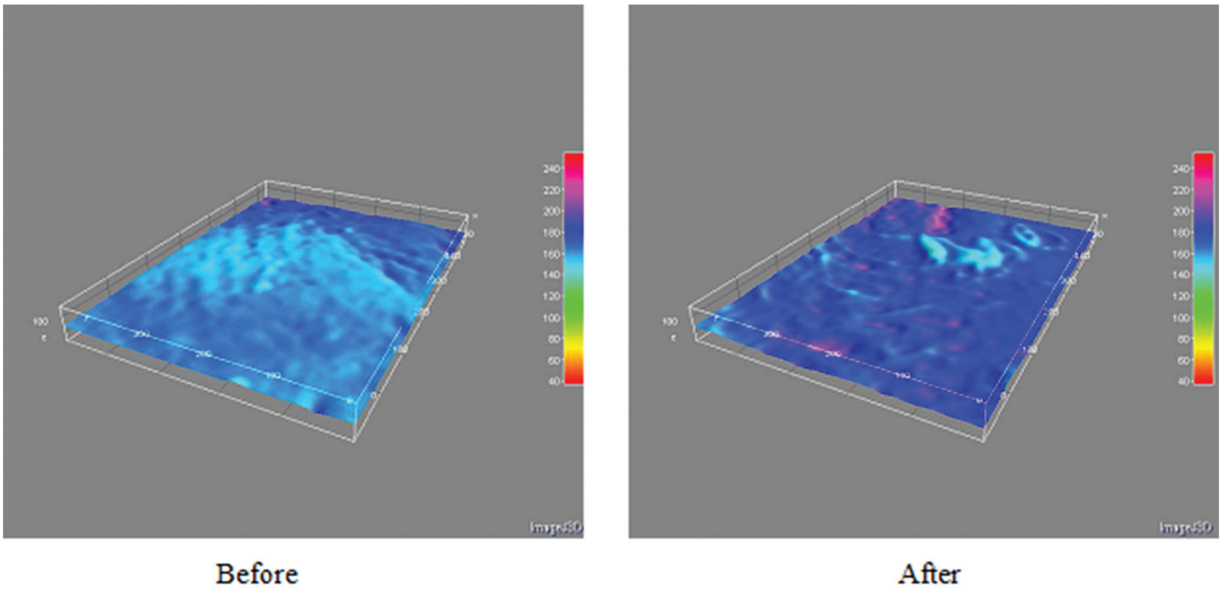
Representative three-dimensional image showing surface topographic features for zirconia sample before and after 3 months' wear simulation cycles.

enamel cusp before and after 3 months wear simulation cycles is shown in Fig. 4.

For the zirconia enamel antagonist group, it was found that the surface roughness mean value before wear was 0.254842±0.002 μm, while after wear simulation, the mean value was 0.258383 ±0.0019 μm, with a surface roughness change mean value of 0.00354±0.00384 μm, as shown in Table 5. The change in surface roughness was nonsignificant, as confirmed by the paired t test (P=0.1477>0.05). Representative 3D image showing surface topographic features for zirconia antagonistic enamel cusp before and after 3 months wear simulation cycles is shown in Fig. 6.

The difference between surface roughness changes recorded for both groups was statistically nonsignificant, as indicated by the unpaired t test (P=0.3832>0.05).

Figure 6



Representative three-dimensional image showing surface topographic features for zirconia antagonistic enamel cusp before and after 3 months' wear simulation cycles.

Discussion

Improvement in dentistry and advance of technologies can be reached by improving dental materials. Biological compatibility, low plaque accumulation, superb aesthetics, properties near to dental tissues and low hardness are essential to present materials used in advanced dentistry. Wear is the loss of the material from surfaces due to mechanical action between two sliding surfaces [14].

PEEK and zirconia are the materials of interest of the current study; hence, they should have both high wear resistance and minimal abrasiveness. Moreover, they should possess wear rate that preferably matches that of tooth enamel.

PEEK and zirconia samples were constructed in discs with diameter 10 mm and thickness 2 mm. This sample configuration was selected because it could be considered as an adequate thickness that would be present in prosthetic appliances [15].

Wear between the enamel of teeth and dental materials is very important, and both materials should have a wear degree similar to that of enamel. Lower premolars were selected as antagonists in this study, as wear between the enamel of teeth and a restoration is very important.

The oral cavity is an intense environment owing to saliva, cyclic loads, and pH fluctuations; thus, the examination of the materials should be in similar conditions to the oral environment. The two-body wear examination was carried out by using a chewing simulator with thermocyclic protocol. The chewing simulator has four chambers to simulate the movements in the thermodynamic condition vertically and horizontally. A loading force of 50 N was applied for 37 500 cycles, which represented the average mastication forces for simulation of the oral cavity [16].

Moreover, water was used as fluid so as to facilitate physiological movement. This approach was also carried out by Kadokawa *et al*. [17].

Material loss in the clinical environment is in general lower than that in laboratory studies. In-vitro wear tests show little correlation to the clinical situation but enable comparative evaluation of different materials under standardized conditions [17].

The findings of this study revealed that, for the PEEK group and zirconia group, there was a statistically nonsignificant difference between the weight changes recorded in both groups. This is a common finding when it came to being used for a long period, as the simulator brought on a reduction in the abrasive resistance [18].

In the PEEK enamel antagonist group and the zirconia enamel antagonist group, there was a statistically nonsignificant difference between weight changes recorded for both groups. Nevertheless, antagonistic enamel wear was much less in zirconia than in PEEK, and this was due to the high wear resistance of zirconia compared with those of enamel [19]. This finding was confirmed by a previous study that used zirconia opposing enamel samples. It was concluded that the effect of antagonistic ceramic wear on human enamel was more than composite resin [20].In addition, the major property of polymers contained in PEEK is flexibility, which allows for more stress absorption by deformation. This finding was confirmed by previous studies examining the wear performance of polymers and ceramics, and CAD/CAM has revealed that CAD/CAM polymers created the least amount of wear of the antagonistic enamel. Moreover, CAD/CAM resins created no enamel cracks [21].

As regards roughness results, the difference between surface roughness changes recorded for both groups was statistically nonsignificant. Nevertheless, it was shown that the samples' roughness was much higher before using chewing simulation. This finding may be attributed to the surface smoothening effect produced by the chewing simulation, which is responsible for reducing the surface roughness [22].

In PEEK and zirconia enamel antagonist groups, the difference between surface roughness changes recorded for both groups was statistically nonsignificant. However, the roughness of the antagonistic enamel was much less in PEEK than in zirconia, and this result could be related to the fact that mechanical properties of PEEK are similar to dentin and enamel. Thus, it has superiority over metal alloys and ceramic restorations. This finding was in concurrence with the findings of other investigators [21–23].

Conclusions

With respect to the limitations of this study, it could be concluded that PEEK is an attractive modern material to use in prosthodontics due to its favorable chemical, mechanical, and physical properties. PEEK when compared with other materials used in dentistry, is more esthetic, stable, biocompatible, and lighter. Compared with zirconia, PEEK showed quite promising effects in terms of antagonistic tooth wear and roughness. PEEK may be highly recommended to be used in areas of high stress, as in cases of weakened abutment teeth, in cases of patients with parafunctional habits.

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Nil.

Conflicts of interest
There are no conflicts of interest.

References

1 Denry I, Kelly JR. State of the art of zirconia for dental applications. Dent Mater 2008; 24:299–307.
2 Jum A. Do they perform well. Restor Dent 2011; 6:2006–2008.
3 Jung YS, Lee JW, Choi YJ, Ahn JS, Shin SW, Huh JB. A study on the in-vitro wear of the natural tooth structure by opposing zirconia or dental porcelain. J Adv Prosthodont 2010; 2:111–115.
4 Alghazzawi TF, Lemons J, Liu PR, Essig ME, Bartolucci AA, Janowski GM. Influence of low-temperature environmental exposure on the mechanical properties and structural stability of dental zirconia. J Prosthodont 2012; 21:363–369.
5 Cattani-Lorente M, Scherrer SS, Ammann P, Jobin M, Wiskott HWA. Low temperature degradation of a Y-TZP dental ceramic. Acta Biomater 2011; 7:858–865.
6 Attia A, Abdelaziz KM, Freitag S, Kern M. Fracture load of composite resin and feldspathic all-ceramic CAD/CAM crowns. J Prosthet Dent 2006; 95:117–123.
7 Stawarczyk B, Ender A, Trottmann A, O?zcan M, Fischer J, Ha?mmerle CH. Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: effect of aging regimens. Clin Oral Investig 2012; 16:1669–77.
8 Zoidis P, Bakiri E, Papathanasiou I, Zappi A. Modified PEEK as an alternative crown framework material for weak abutment teeth: a case report. Gen Dent 2017; 65:37–40.
9 Nawafleh N, Hatamleh M, Elshiyab S, Mack F. Lithium disilicate restorations fatigue testing parameters: a systematic review. J Prosthodont 2016; 25:116–126.
10 Abouelatta OB. 3D surface roughness measurement using a light sectioning vision system. Proc World Cong Eng 2010; 2010:698–703.
11 Giacomelli L, Derchi G, Frustaci A, Bruno O, Covani U, Barone A, *et al.* Surface roughness of commercial composites after different polishing protocols: an analysis with atomic force microscopy. Open Dent J 2010; 4:191–194.
12 Horcas I, Fernandez R, Gomez JM, Colchero J, Gomez-Herrero J, Baro AM. WSXM: A Software for Scanning Probe Microscopy and a Tool for nanotechnology. Rev Sci Instrum 2007; 78:013705.
13 Akaboura A, Fragouli M, Rahiotis C. Evaluation of surface characteristics of dental composites using profilometry, scanning electron, atomic force microscopy and gloss-meter. J Mater Sci Mater Med 2007; 18:155–163.
14 Karakoca S, Yilmaz H. Influence of surface treatments on surface roughness, phase transformation, and biaxial flexural strength of Y-TZP ceramics. J Biomed Mater Res – Part B Appl Biomater 2009; 91:930–937.
15 Rosentritt M, Preis V, Behr M, Hahnel S, Handel G, Kolbeck C. Two-body wear of dental porcelain and substructure oxide ceramics. Clin Oral Investig 2012; 16:935–943.
16 Preis V, Behr M, Kolbeck C, Hahnel S, Handel G, Rosentritt M. Wear performance of substructure ceramics and veneering porcelains. Dent Mater 2011; 27:796–804.
17 Kadokawa A, Suzuki S, Tanaka T. Wear evaluation of porcelain opposing gold, composite resin, and enamel. J Prosthet Dent 2006; 96:258–265.
18 Vedana D, Vedana L, Martins EA, Brodersen P, De Souza GM. Artificial enamel wear after prolonged chewing simulation against monolithic Y-TZP crowns. Mater Sci Appl 2018; 9,381–392
19 Mitova G, Heintzeb SD, Walzc S, Wolld K, Mueck lichd F, Pospiecha P. Wear behavior of dental Y-TZP ceramic against natural enamel after different finishing procedures. Dent Mater 2012; 28:909–918
20 Ghazal M, Kern M. The influence of antagonistic surface roughness on the wear of human enamel and nanofilled composite resin artificial teeth. J Prosthet Dent 2009; 101:342–349.
21 Wimmer T, Huffmann AM, Eichberger M, Schmidlin PR, Stawarczyk B. Two-body wear rate of PEEK, CAD/CAM resin composite and PMMA: Effect of specimen geometries, antagonist materials and test set-up configuration. Dent Mater 2016; 32:127–136.
22 Najeeb S, Zafar MS, Khurshid Z, Siddiqui F. Applications of polyetheretherketone (PEEK) in oral implantology and prosthodontics. J Prosthodont Res 2016; 60:12–19.
23 Skirbutis G, Dzingute? A, Masiliu?naite? V, S?ulcaite? G, Z?ilinskas J. A review of PEEK polymer's properties and its use in prosthodontics. Stomatologija 2017; 19:19–23.