Biomechanics of Different Types of PEEK as Implant Materials for Implant-Retained Mandibular Overdentures

Keywords

Finite Element Analysis
Titanium
Carbon Reinforced PEEK
Ceramic Filled PEEK
Unfilled PEEK

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Received: 01.02.2021
Accepted: 17.06.2021

doi: 10.1922/EJPRD_2286Hassan08

ABSTRACT

Purpose: To evaluate the biomechanical behavior of different types of PEEK as implant materials for mandibular implant-retained overdentures. Materials & Methods: Virtual models of mandibular overdentures retained by two interforaminal implants were simulated. In each model, one implant material was assumed resulting in four models; titanium, carbon-reinforced PEEK, ceramic-filled PEEK and unfilled PEEK models. Unilateral vertical and oblique loads were applied separately. Von-Mises stresses and maximum equivalent strain values were computed. Results: All PEEK implant models induced higher stresses in the cervical portion of peri-implant bone compared to the titanium model. A more homogenous stress distribution pattern along the whole length of the titanium implants was observed compared to PEEK implants. The highest amount of strain values was recorded in the unfilled PEEK implants. Conclusions: Titanium remains to be the most optimum material for dental implants. Unfilled and ceramic filled PEEK might not be recommended as a dental implant material due to the high stresses generated within the implant bodies and cervical part of peri-implant bone under oblique load which might contribute to an increased probability of implant body fracture and marginal bone loss.

INTRODUCTION

Since the introduction of dental implants, titanium has been and still is the most commonly used material for their fabrication. This can be attributed to excellent biocompatibility and superior mechanical properties of titanium and its alloys.[1] However, some drawbacks of titanium were reported in the past few years. There have been reported cases of titanium allergy combined with presence of corrosion particles in the peri-implant tissues.[2,3] Another reported drawback of titanium implants is its dark greyish color that appears in cases with thin mucosal biotype which greatly affects the esthetics especially in the current era where there is increased patients' demand for esthetics and metal-free implants.[4] From a biomechanical point of view, titanium implants have high modulus of elasticity (about 110 MPa) compared to that of bone which is only about 15 MPa which lead to a stress shielding effect, adding another drawback to titanium implants.[5] Stress shielding is defined as a reduction of local bone density over time as a result of a stress reduction, which is caused by implants that are stiffer than the surrounding bone.[5] The higher the elastic modulus of the implant material, the more is the stress shielding effect. This can decrease the normal mechanical stresses in the adjacent peri-implant bone, which are required to maintain proper bone structure.[6]

Therefore, such bone becomes porous and weak and eventually may be resorbed causing prosthetic loosening and implant failure.[6] From there emerged the need to search for alternative biomaterials that can be used for the fabrication of dental implants other than titanium.

Polyether-ether-ketone (PEEK) polymers have been suggested as one of such alternatives.[7,23] The modulus of elasticity of PEEK ranges from 3.9 to 18 GPa depending on whether unfilled or filled PEEK is used respectively. Filled PEEK exhibits a modulus of elasticity close to that of trabecular (10-14 GPa) and cortical (18-20 GPa) bone and has been suggested to optimize load distribution in the peri-implant bone and positively influence the healing process.[8–10] The most common used PEEK composites are carbon re-inforced and ceramic filled PEEK.[9]

Carbon fiber reinforced polyetheretherketone (CFR-PEEK) and ceramic filled PEEK (CF-PEEK) are biointeractive PEEK composites in which carbon fibers and ceramic fillers have been added to the untreated polymer matrix respectively. The fillers increase the mechanical properties and enhance the dimensional and chemical stability of PEEK composites that the materials can be fabricated with high dimensional accuracy and sterilized by common methods such as steam and gamma radiation.[10,11] From a mechanical point of view, the incorporation of fillers can increase the elastic modulus of the unfilled PEEK up to 18 GPa which is close to that of the bone.[12] Therefore, it is hypothesized that it may help to avoid the stress shielding effect, which is experienced with titanium implants and hence the emergence of the term "physiological implant".[13] Nevertheless, a disadvantage of CFR-PEEK compared to CF-PEEK is its dark color owing to the addition of carbon fibers which may be problematic in areas of high esthetic demand.[13]

Despite the above described and potential biomechanical benefit of PEEK implants in reducing the stress shield effect, there is a paucity of data in the literature that evaluates the biomechanical behavior of different types of PEEK, as a dental implant biomaterial in different clinical situations. Therefore, the aim of the current finite element study was to evaluate the influence of different types of PEEK implants on the stress distribution pattern and the amount of strains generated in the implants and peri-implant bone in cases of mandibular implant retained overdentures. The stresses in nylon caps, overdenture prostheses, and denture displacements with different implant materials were also evaluated.

MATERIALS AND METHODS

The study was performed in two main stages:

1. Designing, drawing of the study model using Solidworks software (version 2016, Dassault Systèmes SolidWorks Corporation, Waltham, US)
2. Analysis process using ANSYS Mechanical Workbench (Version 18.1, ANSYS, Inc., Canonsburg, USA).

1. DESIGNING THE 3D MODEL

A 3D virtual model of a mandible with two implants placed in the interforaminal canine region retaining an overdenture was the ultimate design to be reached. Each component was designed separately including cortical bone, cancellous bone, mucosa, overdenture, nylon caps, metal housings and single-piece implants with ball attachments. The mandible was designed by tracing the outline an edentulous mandible over a CBCT of an edentulous patient who was planned to receive an implant overdenture. An informed consent was obtained from the patient to use his CBCT for the purpose of this study. The initial outline of the mandible from top view was traced on Solidworks software using a coronal cut of the mandibular CBCT *(Figure 1b*). Both cortical and cancellous bone were drawn by tracing their outlines on multiple sagittal sections of CBCT in each tooth region and connecting them together to obtain 3D model of half of the mandible. *(Figure 1c and 1d*) The other half was obtained by mirroring the existing half so that 3D virtual model of the mandible was designed *(Figure 1e*).

The thickness of the overlying mucosa was assumed to be 2 mm based on previous studies.[14] Overdenture teeth were designed from the central incisor to the first molar bilaterally. Each tooth was drawn using five sketches; two sketches for mesial and distal proximal contacts and three sketches for body of the tooth *(Figure 1f and 1g*).

Then two implants (3.8 x 12 mm) with ball attachments were placed in the canine region just below the canine tooth of the virtual model *(Figure 1a and 2a*). A bone cylinder (13 mm) with geometry of intrabony part of implants engraved within these cylinders was drawn to facilitate collection of the data and the analysis of results in the peri-implant bone region. The cylinder was splitted into 3 parts: cervical (2 mm), middle (9.5 mm) and apical (1.5 mm). Both the middle and apical parts were considered as cancellous bone while the cervical part was considered as cortical bone *(Figure 2b*). Nylon cap and metal housing were also designed *(Figure 1h and 1i*). Finally, all the drawn parts were assembled together without interference and the final 3D model was obtained *(Figure 3c and 3d*).

2. ANALYSIS OF THE MODEL

The model was then exported to ANSYS Mechanical Workbench (Version 18.1, ANSYS, Inc., Canonsburg, USA) for meshing and analysis as the Solidworks software was unable to solve such large model.

Material properties

All materials in the study were considered homogenous, isotropic and linearly elastic. The modulus of elasticity and Poisson's ratio for each part were defined as obtained from previously published data[15] *(Table 1*).

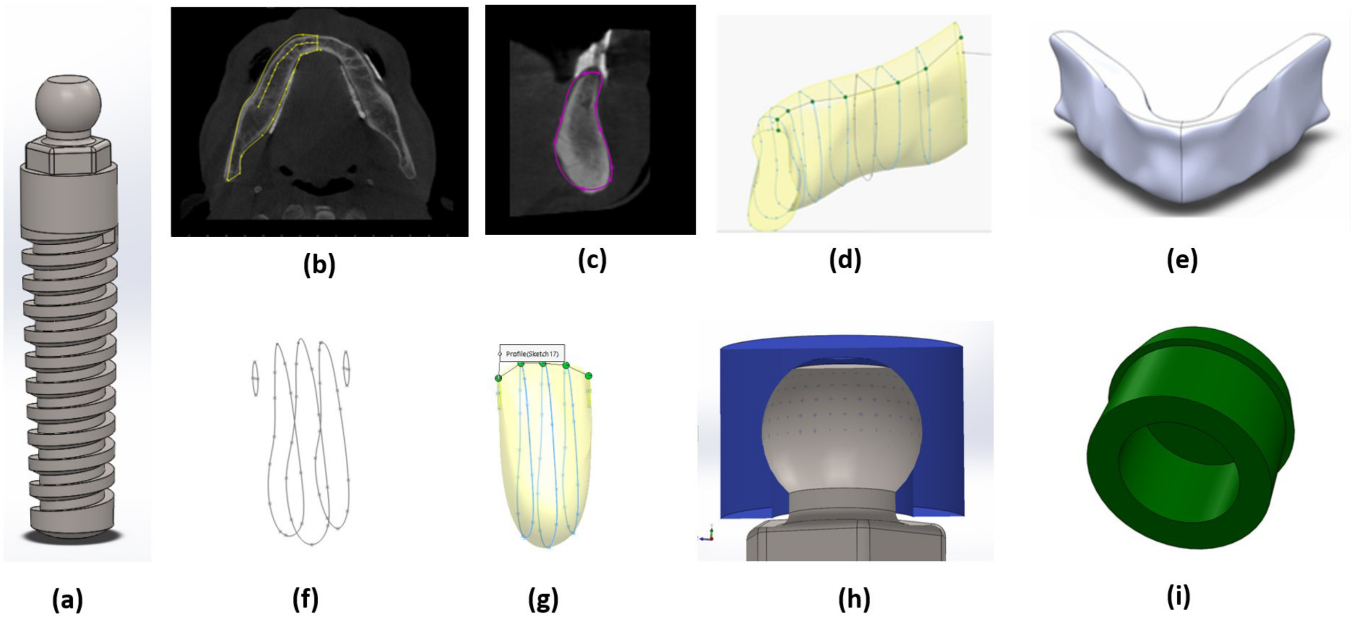

Figure 1: (a) 3D model of the implant with the ball attachment, (b) Tracing the outline of the mandible from the occlusal view, (c) Tracing the sagittal section of the mandible forming 2D-sketch representing thickness of the mandible, (d) Lofting of the 2D-sketches of all areas of the mandible from central to retromolar area to form 3D model of half of the mandible, (e) 3D-model of full mandible after mirroring the second half. (f) Five 2D- sketches of the central tooth, (g) Final 3D tooth after connecting the sketches together, (h) Cross section showing the nylon cap over the head of ball attachment, (i) Metal housing.

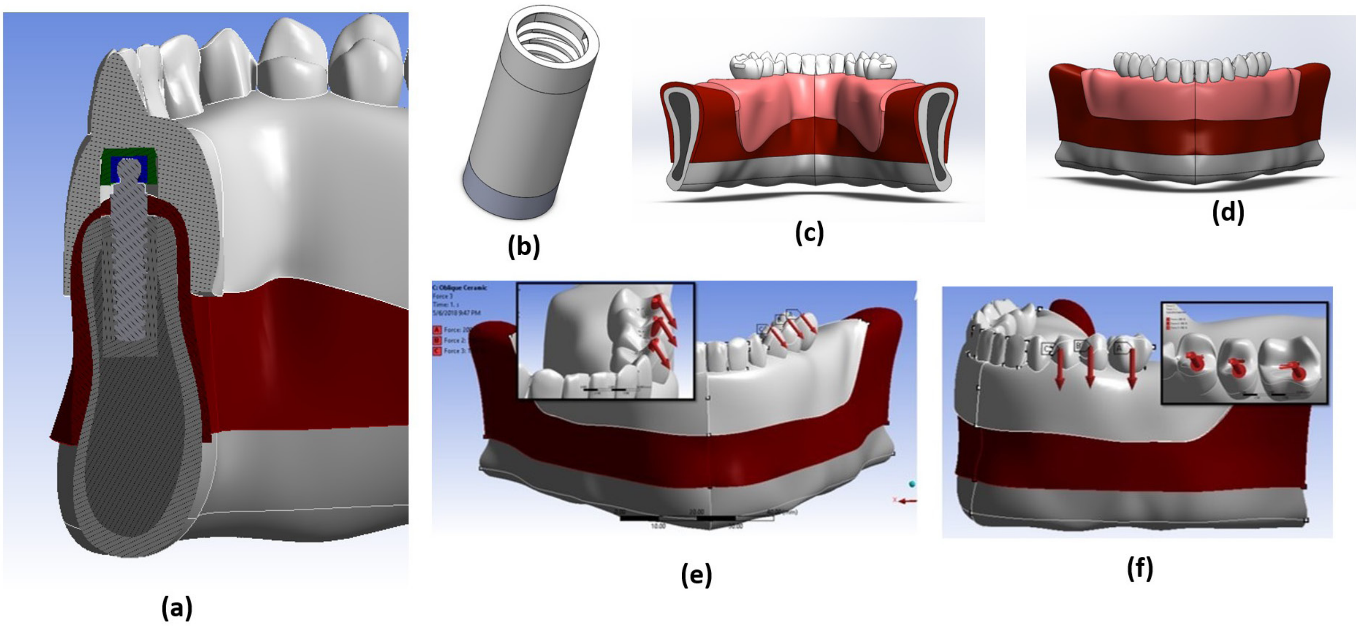

Figure 2: (a) Sagittal section of the model, (b) Bone cylinder with indentations of the implant threads, (c) Front view of the assembled 3D virtual model, (d) Posterior view of the assembled model, (e) Unilaterally oblique load at about 45° to the vertical axis over the lingual inclines of the buccal cusps of the premolars and the first molar, (f) Unilateral vertical load over the central fossae of the premolars and first molar.

Defining contacts

A "bonded contact" was assumed between bone and implants to simulate completely osseointegrated implants with 100% bone-implant contact. A "no separation contact" was assigned for the contact between the mucosa and the fitting surface of the denture base and also between the nylon cap and the head of the ball attachment. This type of contact allows sliding movement of the contacting surfaces over each other. Therefore, the overdenture and the nylon caps were allowed to move freely on top of the mucosa and the implants, respectively.

Meshing the model

A high quality solid mesh was used in this study to create "adaptive coarse mesh" with 3D parabolic tetrahedral solid elements in all models. The models had the same size and number of elements and nodes where number of elements was 35095 and number of nodes was 66209.

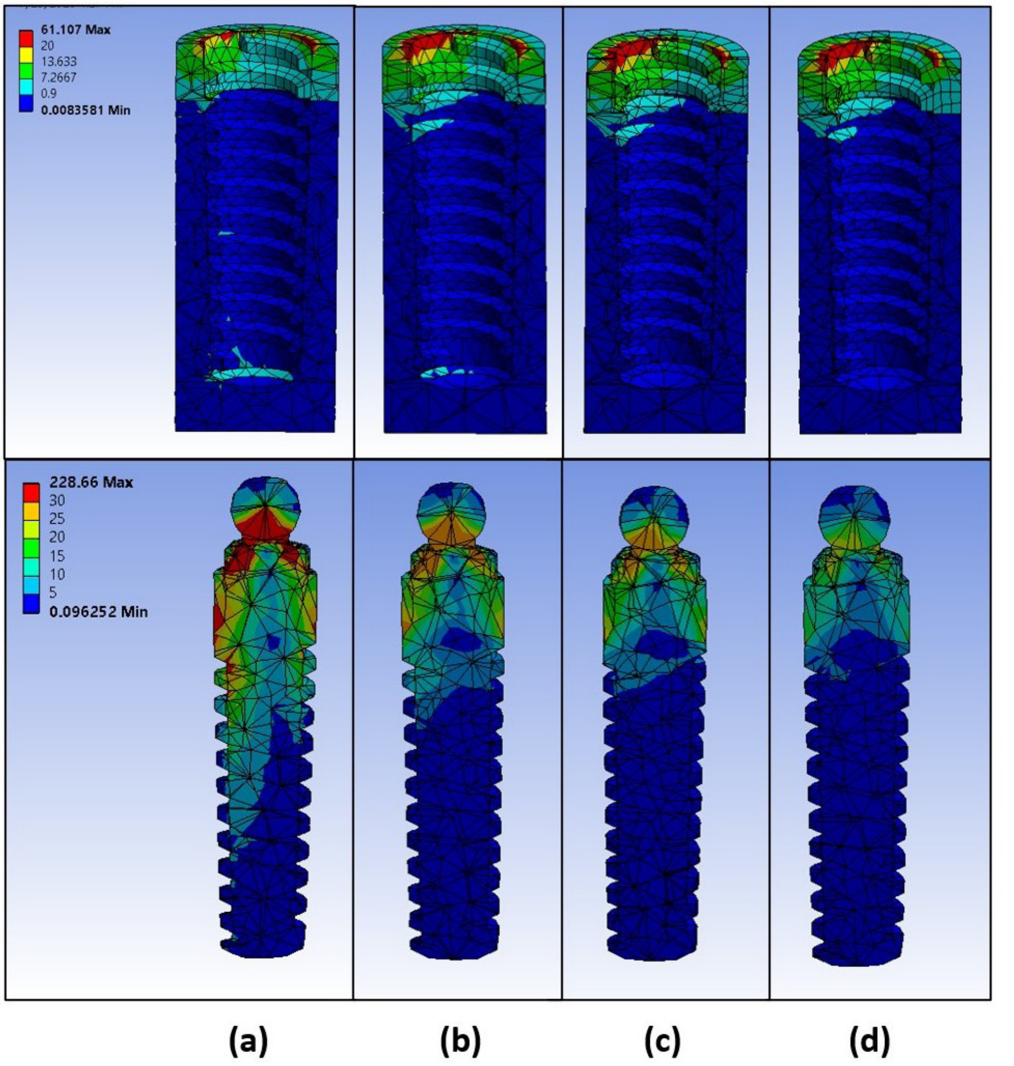

Figure 3: Von Misses stresses in the Peri-implant bone cylinder and in the implants under oblique load: (a) Ti-model, (b) CFR-PEEK model, (c) CF- PEEK model, (d) U-PEEK model.

Restraining the model

A fixed restraint was applied to the inferior border of the mandible to avoid any bodily displacement during load application and allow for strain transmission within the model.

Load Application

The virtual model of each implant material was subjected to unilateral, vertical and oblique load applied separately on each model. A vertical load of 200 N (50 N for each premolar and 100 N for the first molar) was applied on the central fossae of the premolars and the first molar.[16] On the other hand, the oblique load was applied to the lingual inclines of the buccal cusps of the premolars and the first molar with an angle of about 45 degrees to the vertical axis[14] *(Figure 2e and f)*.

The analysis was run by iterative solver to compute von Mises stress and maximum equivalent strain in implants, peri-implant bone, nylon caps, and overdentures prosthesis. Von Mises stresses were selected as it more indicative of the biomechanical ductile behavior of materials under investigation.[17] In addition, several previous studies such as those performed by Chen *et al.*[17] and Sarot *et al.*[18] has evaluated the biomechanical behavior of PEEK implants using von Mises stresses. The displacement of denture in each model was also computed. The von Misses stress was calculated in Mega Pascal (MPa). Displacement of the denture was reported in millimeters (mm).

RESULTS

STRESS DISTRIBUTION AND MAXIMUM EQUIVALENT STRAIN IN PERI-IMPLANT BONE

Stress distribution pattern and recorded values in peri-implant bone is shown in Figure 3 and Table 2. An increase in stress values was recorded in the cervical part of peri-implant bone of all PEEK models by about 39.2%, 40.7% and 40.2 % in CFR-PEEK, CF-PEEK and U-PEEK models respectively when compared to Ti model. The corresponding stress values were 15.1, 21, 21.3 and 21.2 MPa for the Ti, CFR-PEEK, CF- PEEK and unfilled PEEK models, respectively.

Table 1. Material properties of the parts used in the study

Element	Poisson's ratio	Modulus of elasticity (MPa)
Compact bone	0.30	15,000
Cancellous bone	0.30	1500
Mucosa	0.45	10
Titanium	0.30	110,000
Unfilled PEEK	0.40	3900
Carbon reinforced PEEK (30% carbon fibers)	0.35	18,000
Ceramic filled PEEK	0.35	6205
Nylon	0.40	70
Acrylic resin	0.35	2770
tainless steel	0.28	200,000

For the middle and apical portions, a reverse stress distribution pattern was recorded. Ti- implants induced the greatest amount of stresses in these parts compared to all PEEK models. The least amount of stresses was induced in middle and apical portions of U-PEEK model (0.78, 0.19 MPa), followed by CF (0.84, 0.22 MPa) then CFR (0.97, 0.36 MPa)- PEEK implants with concentration of stresses in the cervical portion.

In accordance with stress values, the least amount of generated strains were found in the Ti model under vertical load in the cervical and middle portion with corresponding values of 17.76 and 105.7 με, respectively. On the contrary the highest strain values in cervical and middle portions was recorded in CF-PEEK model with values of 1420 and 557.21 με respectively. On the other hand, the highest recorded strain values in the apical part was recorded in Ti model (322.38 με) opposed to lowest values of (130.1 με) recorded in U-PEEK model *(Table 3)*.

Under oblique load, Ti model showed the least strain values in cervical part (4073 με) and the highest values in middle (3100 με) and apical parts (759 με). The strain values recorded in the cervical part of all PEEK models were almost twice that recorded in Ti model with the highest values recorded in CF-PEEK model (9847 με) *(Figure 4 and Table 3)*.

STRESS DISTRIBUTION IN IMPLANTS

Stress distribution pattern and values in the implants are shown in Figure 3 and Table 2. Under vertical load, titanium implants showed the highest stress values of 63.03 MPa while lowest values of 46.5 MPa were recorded in U-PEEK model representing 26.2% decrease in reported values compared to Ti-model. Under oblique load, the stress values in PEEK models were reduced by 8.3%, 20.5% and 28.6% for carbon reinforced, ceramic filled and unfilled PEEK implants respectively compared to Ti-model. The reported stress values were 228.6, 209.5, 181.5, and 163.2 MPa for Ti, CFR-PEEK, CF-PEEK and U-PEEK respectively.

Table 2. von Misses stresses in peri-implant bone and within implants in the loaded side under vertical and oblique loads.

Stress (MPa)	Cervical	Middle	Apical	Implant itself
Under vertical load				
Titanium implants	15.14	1.57	0.48	63.03
Carbon reinforced PEEK	21.08	0.97	0.36	57.59
Ceramic filled PEEK	21.31	0.84	0.22	50.46
Unfilled PEEK	21.23	0.78	0.19	46.52
Under oblique load				
Titanium implants	61.11	4.65	1.14	228.66
Carbon reinforced PEEK	118.96	3.02	0.78	209.57
Ceramic filled PEEK	147.70	2.34	0.55	181.56
Unfilled PEEK	145.63	1.97	0.49	163.26

MAXIMUM EQUIVALENT STRAIN IN IMPLANTS

The highest amount of strain values were reported in the U-PEEK implants under vertical (11,927 με) and oblique load (41,860 με) while the least values were reported in Ti-implants with corresponding values of 573 με and 2181 με respectively as shown in Table 3 and Figure 4.

MAXIMUM EQUIVALENT STRAIN IN NYLON CAPS AND OVERDENTURE PROSTHESIS

The highest strain values in nylon cap were recorded in Ti model under both vertical (112,810 με) and oblique (190.010 με) loads. On the other hand, U-PEEK model displayed the lowest strain value of 165.470 με under oblique load, representing 13% decrease in amount of nylon cap deformation compared titanium model *(Table 3)*.

For the overdenture prosthesis, all the study models showed almost the same values of generated strains in the overdenture prosthesis *(Table 3)*.

Table 3. Maximum equivalent Microstrain values in the loaded side under vertical and oblique loads.

Microstrain	Cervical	Middle	Apical	Implant	Nylon cap	Overdenture
Under vertical load						
Titanium implants	17.76	105.79	322.38	573	112.810	11.984
Carbon reinforced PEEK	1405	649.67	210.19	3199	111.840	11.985
Ceramic filled PEEK	1420	557.21	144.59	8131	110.030	11.986
Unfilled PEEK	1415	517.68	130.10	11.927	108.720	11.987
Under oblique load						
Titanium implants	4073	3100	759	2181	190.010	31.357
Carbon reinforced PEEK	7931	2020	517	11.643	183.470	31.476
Ceramic filled PEEK	9847	1557	369	29.261	172.400	31.677
Unfilled PEEK	9708	1315	331	41.860	165.470	31.807

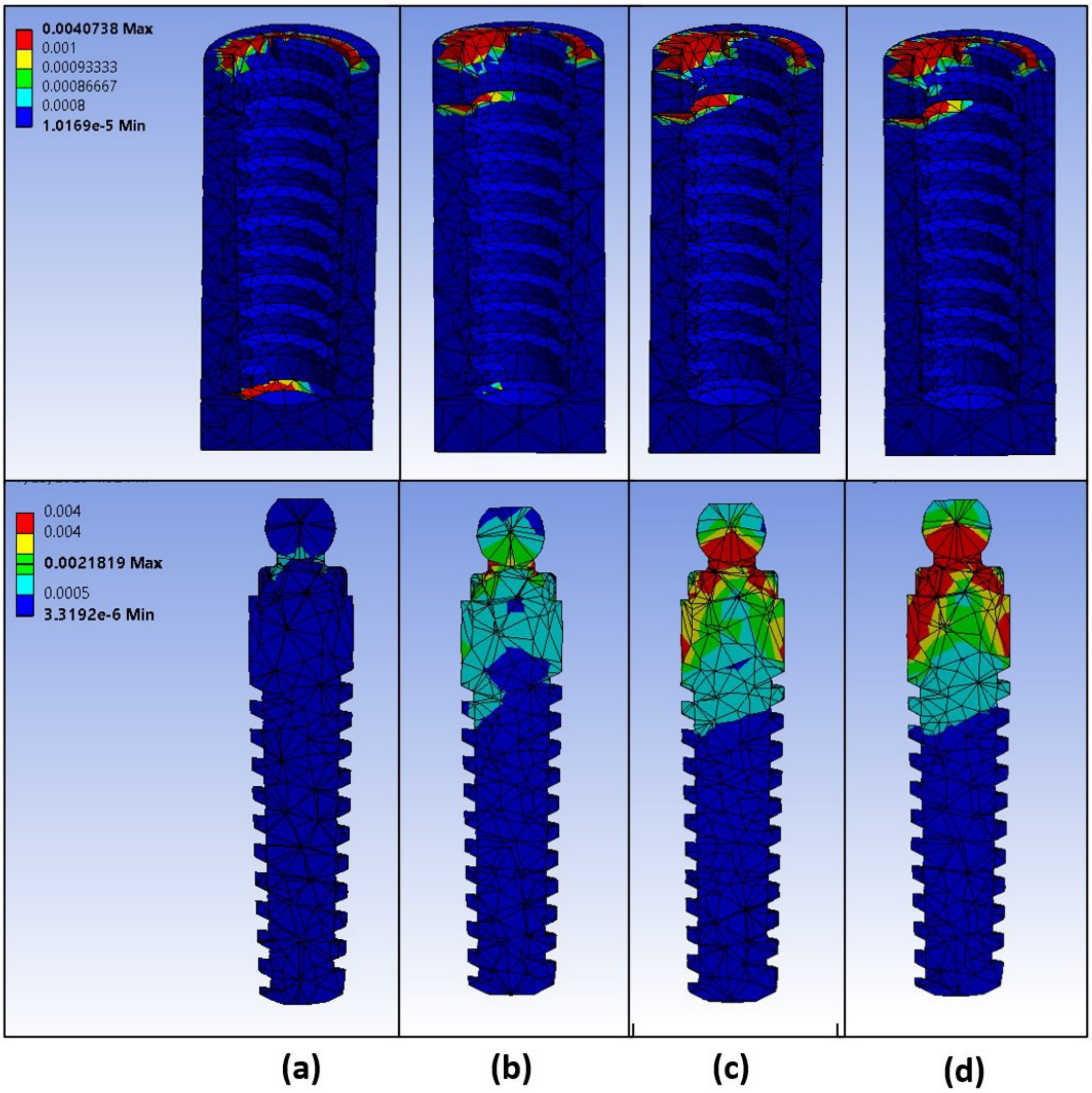

Figure 4: Maximum equivalent strain in peri-implant bone cylinder and in the implants under oblique load: (a) Ti-model, (b) CFR-PEEK model, (c) CF- PEEK model, (d) U-PEEK model.

OVERDENTURE DISPLACEMENT

There was minor negligible difference in the values of overdenture displacement under both vertical and oblique load between the different models as shown in Table 4.

DISCUSSION

The aim of the current study was to evaluate the stress distribution pattern and the amount of microstrains generated in the implants and peri-implant bone in case of different implant materials retaining mandibular overdenture prosthesis. Furthermore, the microstrain values in nylon caps, and overdenture prosthesis as well as the amount of denture displacement was recorded for each model. Based on the findings of this study, the highest stress values were recorded within the cervical portion of the peri-implant bone followed by middle then the apical parts in all study models under both vertical and oblique load. This can be explained through the principle of "composite beam analysis" which states that when two materials with different elastic moduli such as bone and implant are placed in contact and one material is subjected to load, the greatest amount of stresses will be localized at the first point of contact between the two materials.[5] In case of dental implants, this point is the cervical portion of bone. As the elastic modulus of the PEEK implants ranges from 3.9 MPa for the unfilled to 18 MPa in the filled forms, the mismatch in the elastic modulus between PEEK implants and bone will be smaller than that between titanium implant and bone with titanium elastic modulus being 110 MPa. Thus, it is not surprising that the PEEK implants induced greater amount of stresses in the cervical portion of peri-implant bone than titanium.[18] This greater amount of stresses induced in the cervical portion might, in actual clinical situations, increase the risk of peri-implant marginal bone loss.

On the other hand, PEEK implants induced lower stress values in the middle and apical portion of the bone compared to titanium implants. This behavior of stress distribution is in line with the basic principle of the energy conservation where the energy can neither be created nor destroyed.[19] Thus, under the same load conditions, the implant that transmits more stresses to the first point of contact with bone would transfer less to the rest of the bone. As PEEK implants transfer more stresses to the cervical portion of bone, less amount of stresses would be transmitted to the middle and apical parts and vice versa in case of titanium implants *(Table 2)*.[11] The more homogenous pattern of stress distribution observed in the peri-implant bone of titanium implants may be more desirable in a clinical setting to minimize cervical peri-implant bone loss. This pattern of stress distribution can be attributed to reduced deformation of titanium implants compared to PEEK implants.[10]

As per Frost mechanostat theory[21] for physiologic bone remodeling, a certain amount of strain is needed in response to induced stresses to allow for remodeling process. Frost defined a microstrain level that is less than 200 με as one which will cause disuse atrophy and values over 4000 με as a pathological overload that stimulate bone-fatigue failure beyond which microfractures can be produced, and subsequently can result in bone resorption and loss. [22,23] In our study, the microstrain level in all PEEK models under vertical load were between 500 – 1500 με that would stimulate physiological bone remodeling whereas titanium model showed microstrain levels below 200 με which might cause disuse atrophy according to Frost theory. Nonetheless, this should not be a point of concern considering that the generation of pure vertical load intra-orally is a very rare occurrence. However, under oblique load in all PEEK models, the microstrain levels in the cervical portion of peri-implant bone was very high with values above 4000 με, which may induce bone fatigue and failure and subject the crestal bone to high risk of microfractures and crestal bone loss. On the contrary, microstrain values in titanium model in the cervical part were within the physiological bone remodeling range thus, suggesting reduced possibility of microfractures and chances of disuse atrophy.

The results also showed that the U-PEEK implants have experienced the least amount of stresses generated in the implant body followed by the CF, CFR- PEEK models and finally Ti implant model which exhibited the highest stresses values within the implant. This can be explained by the direct relationship that exists between Young's modulus and the amount of stresses induced within the material. A more rigid implant absorbs more stresses for the same amount of load and implant design.[24] On the other hand, there is an inverse relation between the elastic modulus of the implant material and the amount of strain developing within the implant. This explains the findings of this study where titanium implants demonstrated the least amount of strain developed within the implant body and the U-PEEK implants with the lowest elastic modulus values exhibited the highest strain values. [25,26]

The unfilled and ceramic filled PEEK implants used in this study showed maximum stress values of 163.2 and 181.5 MPa under the oblique load, which were well above the flexure strength reported for both types of PEEK material of 125 and 170 MPa respectively. This is suggestive that the unfilled and ceramic filled PEEK implants may be prone to fracture under

Table 4. Displacement of the overdenture in millimetres under vertical and oblique loading.

Displacement (mm)	Under vertical load	Under oblique load
Titanium implants	0.38	0.94
Carbon reinforced PEEK	0.39	0.96
Ceramic filled PEEK	0.39	0.97
Unfilled PEEK	0.39	0.98

oblique load in clinical situation. On the other hand, the maximum stress values of 209.5 MPa induced in carbon reinforced PEEK implant were well beyond its reported flexural strength of 300 MPa suggesting the possible safe clinical use of this type of implant material without the risk of implant fracture.

The nylon caps demonstrated the best performance in terms of reduced material deformation with PEEK models compared to titanium model. On clinical ground, this previous finding may be indicative of longer lifetime of nylon caps and reduced maintenance requirements needed with PEEK implants.

It should be mentioned that no matter how precise the simulation was performed, an *in-vitro* study could never fully represent the actual clinical situation; the modeled elements were considered homogenous, isotropic and linearly elastic which is not the actual case. However, it helps in understanding the basic mechanical behavior of the material used and gives an indication of its behavior in an intra-oral situation. Furthermore, finite element analysis, as other *in-vitro* investigations, is considered a good comparative tool between two or more situations, which in the current study provided deeper understanding of the difference in mechanical behavior between titanium and different type of PEEK implants. Future in-vivo studies are yet recommended to evaluate the findings of this study and enable the drawing of evidence-based recommendations regarding the clinical use of PEEK implants.

CONCLUSIONS

Based on findings of this study and from biomechanical point of view, titanium remains to be the most optimum material for dental implant fabrication. The only PEEK material that might be considered as a potential alternative to titanium implants in patients allergic to titanium or seeking metal-free option is carbon fiber reinforced PEEK among other non-metallic implants available in the market. Unfilled and ceramic filled PEEK might not be recommended as a dental implant material due to the high stress values generated within the implant bodies and cervical part of peri-implant bone under oblique load which might contribute to increased microstrain levels beyond the physiological bone remodeling values and increase the probability of implant body fracture.

CONFLICTS OF INTEREST

The present study was self-funded, and the authors report no conflict of interest.

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