Finite Element Analysis of Elastic Stresses on Oral Mucosa and Cortical Bone by Maxillary Poly (Etheretherketone) (PEEK) Removable Partial Denture (RPD)

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Abstract-

Background- Use of Polyetheretherketone (PEEK) for the removable partial dentures (RPD)frameworks is gaining popularity. But weather it distributes the stresses in a similar way like cobalt-chromium alloy (CoCr) or titanium alloy (Ti) is still unclear and needs assessment.

Purpose: The aim of the study was to evaluate the amount of stress distribution on oral mucosa and cortical bone of alveolar ridge by maxillary poly (etheretherketone) (PEEK) removable partial denture (RPD) using 3-dimensional finite element models and compare it with stress generated by conventional cobalt-chromium (Co-Cr) RPD and titanium (Ti) RPD, in distal extension cases.

Materials and Methods: Patient's intraoral data were obtained via CBCT and master model scan. Virtual RPD framework model and underlying oral mucosa with cortical alveolar ridge was produced for a Kennedy Class II arch modification 1, having first pre-molar as primary abutment. Designing was done following conventional guidelines, using 3Shape dental system. RPD frameworks were designed. Three materials were considered, one with PEEK, second with Co-Cr and third Ti. Movement of the rest on the tooth-supported side was restricted in all directions. For calculating the elastic stresses on mucosa, movement of the alveolar surface of the mucosa and the occlusal rest on the abutment adjacent to the edentulous ridge was fixed in a vertical direction and for stresses on cortical alveolar bone the movement of oral mucosa was fixed in all direction along with the occlusal rest on the abutment adjacent to the edentulous ridge. The Vertical and buccally oblique biting forces were applied simultaneously on each of the locations representing two missing teeth. The FEA was done for analyzing the stress transferred from the RPD frames.

Results: In the 3 tested materials, framework made of PEEK has the lowest maximum von Mises stress followed by CoCr and Ti- 18.736 MPa,66.657 MPa and 68.323 MPa respectively, greatest maximum von Mises stress on the mucosa0.12625MPa and alveolar bone 1.6369 MPa. PEEK has the largest displacement of the framework (free-end displacement of the framework)0.039954 mm, which was larger than CoCr alloy (0.024367mm) and Ti alloy(0.004607mm) and its deformation along with the deformation of complete model assembly.

Conclusion- PEEK framework has the maximum displacement under load which is not good for RPD stability, also as it conducted more stress on mucosa and alveolar bone, which will result in fast resorption of residual alveolar ridge.

Key words- RPD, Stress, Free end saddle, Finite element analysis, Co-Cr,PEEK.

Tob Regul Sci.™ 2021;7(6-1): 7005-7015
DOI: doi.org/10.18001/TRS.7.6.1.29

Introduction-

Movements of a Removable Partial Denture (RPD) under occlusal loading may cause injury to the mucosa as well as cortical bone of the residual alveolar ridge. RPDs for distal extension cases such as Kennedy Class I, II also generate significant stress on the free-end abutment. Due to the difference between the resiliency of teeth (periodontal ligament) and mucosa, the stress response also differs, and it is likely to cause excessive distal and medium-direction torque, resulting in excessive stress on mucosa, residual ridge resorption and loosening or even detachment of the abutment 1-3. The rigidity of the RPD frameworks plays an important role in such scenario and it should be evaluated in relation to the denture movements and stress distribution created in the mucosa. The rigidity of an RPD framework is influenced by its width of its components, thickness, connector design,4,5ridgearc spancurvature,5,6 and properties of alloy forb framework like elastic modulus.

Conventional removable partial denture (RPD) frameworks are often made of cobalt chromium alloys (Co-Cr), which has major drawback of esthetics and allergic reactions also oral galvanism, and biofilm plaque formation has been described. A substitute for patients with esthetic and allergic issues to Co-Cr alloys is a metal-free RPD.7-9 Nonmetal denture framework materials comprises of large body of organic polymers with desirable physical and chemical properties. One such material is polyetheretherketone (PEEK). It has anti-allergic property, good polishability, low plaque affinity, and good wear resistance. Basically, PEEK is a semi-crystalline organic polymer which is biocompatible with stable chemical properties, high temperature resistance, and easy mechanical processing properties10,11. Framework made up of polymer consists of a modified poly(etheretherketone) (PEEK) polymer, bio high-performance polymer (BioHPP) framework combined with acrylic resin denture teeth, and a conventional acrylic resin denture base. This type of framework in a class I and II RPD may help in reducing the rotational torque and stresses on abutment teeth, mucosa and cortical alveolar ridge.12,13 The PEEK has also showed better mechanical properties when used as denture base and provides effective retentive force at deeper undercut without tendency to fracture.14

Studies have been conducted with PEEK in relation to implants and various designs of RPD and its effect on stress generated on abutments had been analysed but elastic stresses on mucosa and cortical bone has not been clearly studied.

There are variety of methods to determine the stress generated on tissues for example photoelasticity assessment, measurement sof strain gauge, optic methods, and computational methods 15. Computational methods, has better efficiency with reliability, if chosen carefully. In the present study, we used Finite Element Analysis (FEA) which was specifically suitable for the study. FEA basically is a numerical method and use methods from the calculus of variations to estimate a solution by reducing an associated error function after subdividing a big system into small parts and then constructing them into a bigger system of equations that represents the whole problem16. FEA has been used widely for predicting the biomechanical behavior of different prosthetic bodies in oral biologic conditions17, like dental implants18, fixed and removableprosthesis19, implant assisted RPD20 and bone metabolism21. This method is relatively better for studying mechanical behaviors of tissues which would be difficult in vivo studies.

So this study was conducted to determine the amount of elastic stress generated and its distribution on oral mucosa and alveolar ridge by maxillary poly (etheretherketone) (PEEK) removable partial denture (RPD) using 3-dimensional finite element models and compare it with stress generated by conventional cobalt-chromium and titanium RPD.

Materials and Methods-

This study was conducted in King Khalid University as a joint venture of college of dentistry and college of engineering. Ethical clearance was obtained from the university ethical clearance committee. The study was conducted in pre-decided steps as in flow chart (Fig.1).

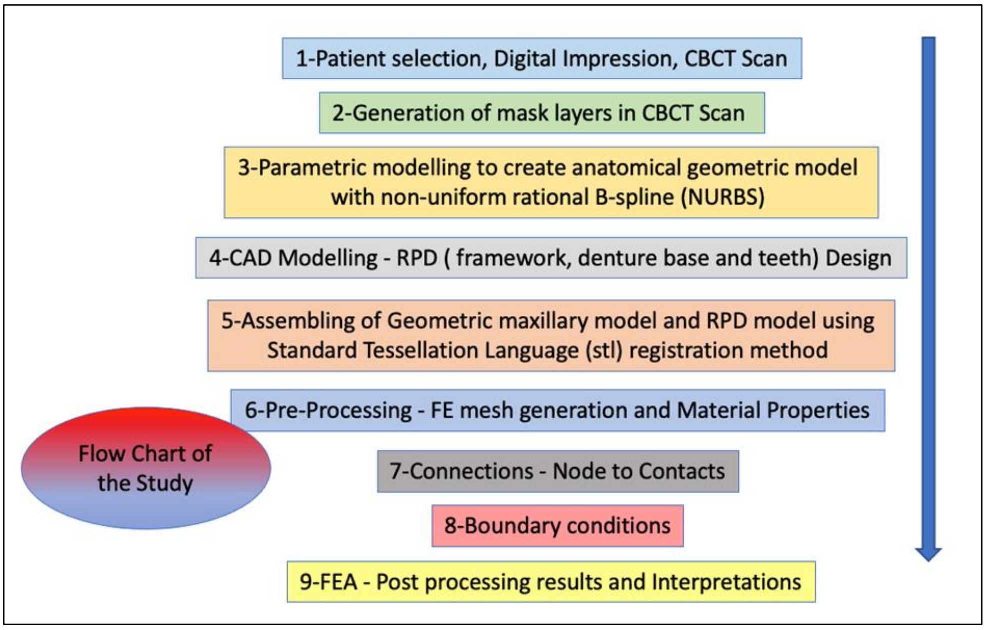

Fig-1 Flow chart

Fabrication of FEA model by Superimposition technique-

A 3-dimensional FEA solid model of maxillary jaw was constructed using clinical CBCT data of a 58-year-old Saudi national with unilateral distal extension i.e. Kennedy Class II modification 1. Oral examination revealed a resorbed maxillary residual alveolar ridge with #14,15,16, 26, 27 and 28 missing (FDI standard), and no other abnormality was discovered among the remaining teeth.

The maxillary arch was scanned with CBCT (3D Accuitomo scanner, Morita, Kyoto, Japan) at a 0.25-mm-slice thickness and 1-mm scan increment in 401 slice images in DICOM format, at 120 kVp, 18.45 mAs, and 20 s exposure. Two segmented masks (bone and mucosa) were further processed in 3D parametric modelling software Rhinoceros 4.0 (Robert McNeel& Associates, Seattle USA) to create anatomical geometric models with non-uniform rational B-spline (NURBS- mathematical model using basis splines (B-splines) that is commonly used in computer graphics for representing curves and surfaces) and were further saved in stl format.

The maxillary model was prepared upto the floor of maxillary sinus to provide a flat base for FEA. In order to enable uniform comparison, the digital impression

of the maxillary arch was done using intra-oral scanner (i-itero) and was transferred as stl file to a CAD software in which the RPD (frame work, denture base and teeth) was designed and stored in stl format. Following the design specifications of conventional RPD for Kennedy Class II modification I chief researcher made the design (and same was approved by two experienced prosthodontists as well as technician together) by using 3shape Dental System software (Dental system 2017, Denmark). Frameworks designs was as follows: Framework A: an RPA (mesial Rest-guide Plate- Aker clasp) clasp set in tooth # 25 and indirect retainer was provided at # 13 with cingulum rest seat and T-bar clasp, and C-clasp on #17. Anterio-posterior palatal strap was used as major connector and mess shaped minor connector was used on the edentulous residual alveolar ridge.

The final stl files of geometric maxillary model and designed RPD were assembled using the Standard Tessellation Language (stl) registration method both manually and automatically registering the stack of stl slices of RPD on the stacks of stl files of maxillary mask model. The final assemblies were exported to ABAQUS6.9.2(Dassault Systems, Tokyo Japan --(2016, SIMULIA Co, USA)) for FE meshing. To ensure the numerical accuracy, adaptive mesh was employed and a mesh convergence test was carried out, as (Li etal.,2004,2005). In the present study, the final meshes contain 92950 Element Count and157026Node Count and 6 degrees of freedom using quadratic tetrahedral elements with hybrid formulation (C3D10H) to ensure smoothness of contact interfaces for the Linear Static Analysis.

The 3D FE model of maxillary arch (mesh generation) (Fig.2) was created with utmost accuracy by exact transfer of mucosal thickness throughout the arch with the help of mask modelling. The mucosa thickness was defined with the vertical distance between the mandibular bone surface and the mucosal surface. The 3D FE organic model obtained with this technique could provide a more accurate geometrical morphology and thickness of mucosa, which is crucial for RPD simulation.

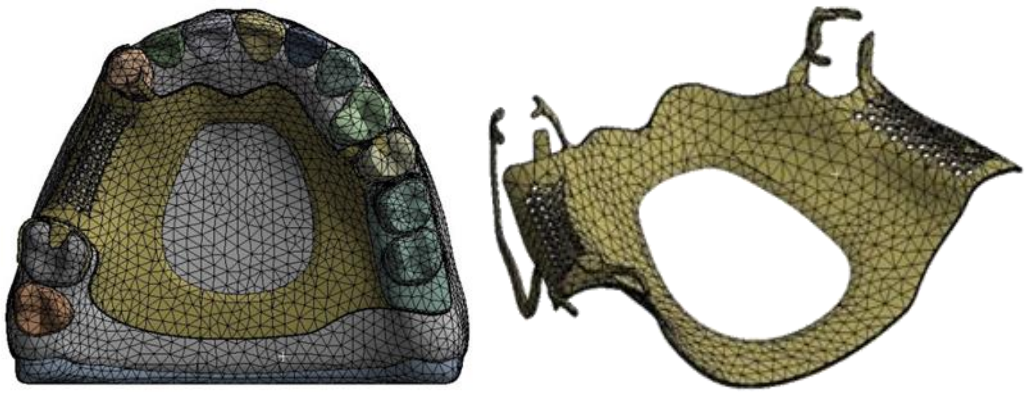

Fig.-2 3D FE model of maxillary arch (mesh generation)

After the generation of mesh model the material properties were applied. The materials and tissue simulators used in the study showed different mechanical and physical characteristics. These materials were considered isotropic and homogeneous to simplify the calculations, and the elasticity modulus and Poisson's ratios were acquired from the literature. Table 1 showed the elastic modulus and the Poisson ratio for each material 22-24.

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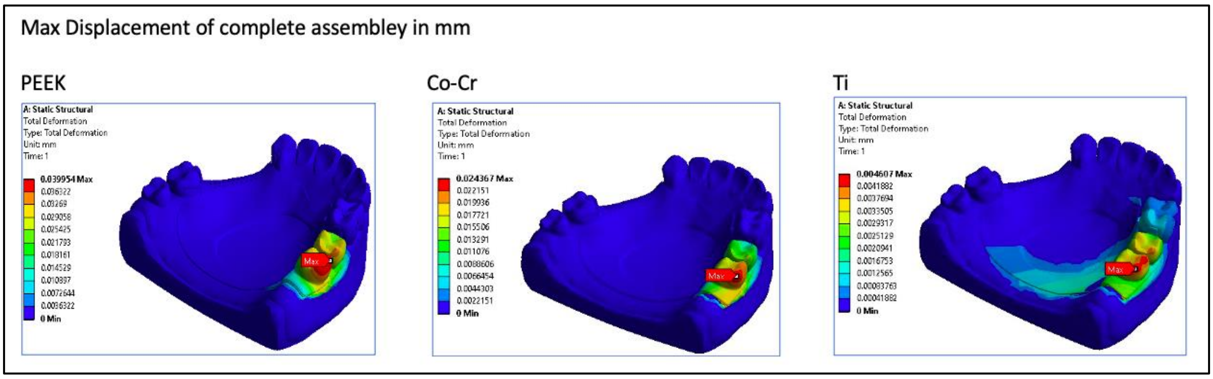
Material	Elastic Modulus (MPa)	Poisson Ratio
PEEK -	4,100	0.40
Denture Tooth -	1,960	0.30
Co-Cr Alloy -	235,000	0.33
Titanium Alloy -	11 * 104	0.35
Mucosa -	3.45	0.45
Alveolar Bone -	13,700	0.30

The denture teeth and denture base were considered as position constraints and boundary conditions were applied for the proper analysis. The interfaces between the clasps and the remaining teeth were modeled as frictional contacts with appropriate friction coefficients (μ = 0.1), and the friction coefficients between the denture base and mucosa was assumed as μ = 0.01. 22,23. The augmented Lagrangian algorithm was adopted to simulate the denture-mucosa contact, with a low frictional coefficient assumed as 0.1 to mimic proper lubrication in the oral Environment (Prinz etal.,2007). Localized masticatory load was applied to simulate an occlusal force, both vertical (20 N) and oblique load (15 degree to long axis of teeth- 20 N) was applied to the center of occlusal surface of both the artificial first and second molar 25 Although different masticatory activities (e.g. grinding) with various loading patterns may affect the optimization outcome, but the effects of other masticatory activities are less significant compared to the direct biting force because of the magnitudes 26. The ANSYS Work bench program was used for finite element analysis, following were investigated: the von Mises stress values of the mucosa, frameworks, alveolar bone and the displacement of framework and total deformation of framework and whole model as a complete assembly (Fig.3).



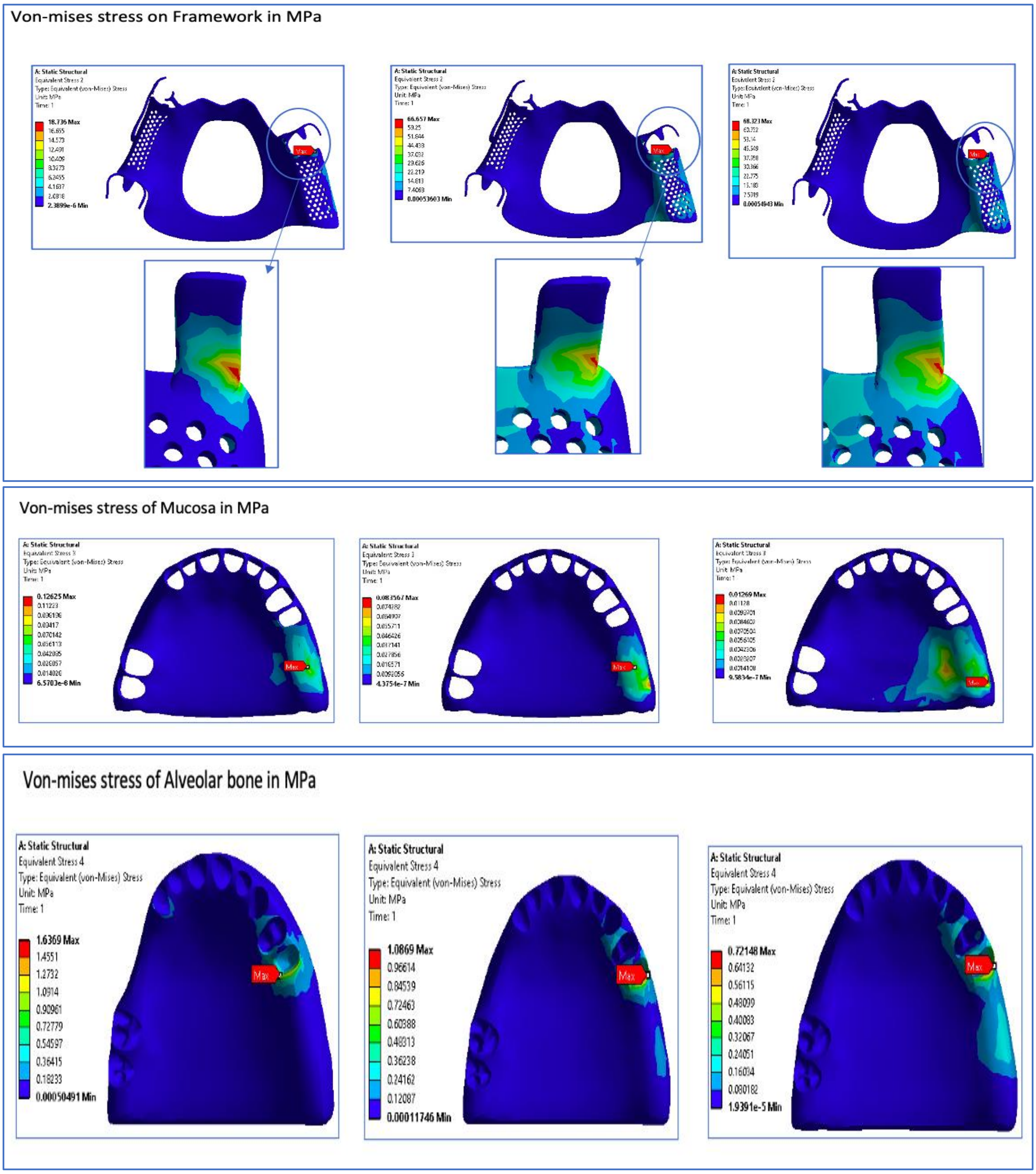


Fig.3- Von Mises stress of mucosa, framework, displacement of framework and complete model assembly under vertical and oblique loading.

Results

Compared with CoCr and Ti-6Al-4V alloy, PEEK framework has the lowest maximum von Mises stress. The greatest maximum von Mises stress on the mucosa, alveolar bone the largest displacement of the framework and its deformation along with the deformation of complete model assembly.

The maximum von Mises stresses of the PEEK, CoCr alloy and Ti alloy framework were 18.736 MPa,66.657 MPa and 68.323 MPa respectively. The maximum stress of PEEK was 27.42% that of the Ti alloy and 26.12% that of the CoCr alloy, suggesting that the PEEK significantly reduced the internal stress of the framework.

On comparison of maximum von Mises stress on the framework statistically significant differences were found between the PEEK and CoCr and PEEK and Ti, but no significant difference was found between CoCr and Ti.
The maximum von mises stress of the mucosa of PEEK, CoCr alloy, Ti alloy, groups were 0.12625, 0.083567 and 0.01269 MParespectively, indicating that PEEK was less conducive in the protection of mucosa. All the stress distribution positions of the mucosa were located at the disto-buccal aspect of the free end saddle. Similarly, the maximum stress of the alveolar bone of PEEK group was1.6369, CoCr was1.0869 and Ti 0.72148, with statistically significant difference in values of PEEK, CoCr and Ti.
As for framework maximum displacement, the free-end displacement of the framework made by PEEK was the largest with the value of 0.039954 mm, which was significantly larger than Ti alloy(0.004607mm) and CoCr alloy (0.024367mm). The deformation caused in framework and complete model as an assembly was maximum in PEEK followed by CoCr and Ti.

Discussion

To restore the missing dentition the RPD is one of the most used prostheses and is used extensively in distal extension cases viz. Kennedy Class I and II. As a prerequisite denture should not only replace but restore the function. The framework should be retentive, stable and prevent further deterioration of soft and hard tissue. In distal extension case both tooth and tissue provide support. The abutment provide retention with different types of clasps and the mucosa, alveolar bone and other tissues provide support for the denture. It is important for the denture base to cover supporting tissues and uniformly distribute the masticatory force, failing to do so results in local tenderness or excessive absorption of the alveolar bone, affecting the use of denture 2,3. Therefore, a proper framework design should take into consideration not only the retention and stability of the denture, but also the stress on the significant tissues.
The RPD framework flexibility especially in distal extension case results in varied range of forces that would be transmitted to the underlying mucosa and alveolar bone, resulting in resorption of the tissues. This study assessed the effect of RPD PEEK framework over the oral tissues. The Kennedy Class II modification 1, case was selected and a virtual RPD framework was designed taking into consideration the basic design concept and 3 material (PEEK, Co-Cr, Ti) properties were incorporated and assessed by FEA. For framework, an RPY (Rest-Plate-Y bar) clasp was set in the premolar #24 and an RPI (Rest-Plate-I bar) clasp was set in the canine #13 to act as stress-breaker and reduce both distal movement of the abutment and exposure of clasps. Aker clasp was set in the on molar #17 to enforce retention.
Stress on periodontal ligaments of abutment tooth is an important parameter to be considered while designing the framework because it has been reported that the resorption of root and remodelling of bone starts with stress generated on the PDL27,28. In a previous study it has been reported that the under similar loading conditions, PEEK framework demonstrated the best protection function on the PDL, which may be particularly suitable for patients with poor periodontal conditions 29,30.
In the present study the patient's abutment was in good periodontal health and assessment of stress was done on the mucosa and alveolar bone. In our patient's case, which was Kennedy Class II modification 1, 2 molars #26, and #27 were missing in distal extension side and #14,15 and 16 were missing in modification side. There were more missing teeth on the right side of the maxillary jaw than the left side. In the terms of mechanics, the teeth bounded right side was stable as the retainers on the abutment were controlling the movement but on the free end saddle side i.e. left side the stress arm of dislocation force was longer which would result in sinking of the framework in apical direction. Therefore, regardless of the framework material, the stress of the framework was larger on the left side, and the stress concentration point of the framework was located at the right-angle turn between the clasp (Guide plate of RPA clasp) and minor connector (Fig. 2), which was consistent with previous research31
The stress of PEEK framework was smaller and was distributed more evenly when compared to Co-Cr and Ti alloys. Conversely, the dislodgment of the distal end of the PEEK framework was higher, which was a drawback concerning

the stability of the RPD and may cause failure. A preceding case report32 stated that PEEK framework may results in lesser retentive force compared to metallic RPD because of low modulus of elasticity 10. The greater dislodgment may also decrease the chewing efficiency of the individual. In previous studies, it was reported that, stresses below the denture produced by forces of mastication were about 80–300 Kpa33–37. Considering the impact of the differences in foundation and occlusal loads on stress values, there is a corelation between the previous studies and the present work. As revealed in the result, PEEK RPD frameworks exerts substantially greater stress on mucosa when compared to other two studied materials, which may result in enhanced absorption of the residual alveolar bone38. Former studies reported pain threshold of mucosa as 0.63 MPa39,40, which called for caution to be taken while using PEEK frameworks in distal extension cases.

The present study has presented a new technique to determine the 3-D FEA model of mucosa for investigating the mechanical behaviors of RPD in oral cavity. One of the conventional techniques 31,41,42 is to use only CBCT scan data to create the mandibular bone and replicate the mucosa as a 2 mm thickness. This method basically explain the details of alveolar bone and its dentition at a advanced level; but, the single 2 mm thickness technique of mucosa consideration provides very less information about the oral mucosa, which means that this way of making the mucosal model was not correct especially in Kennedy's class I and II cases. Few methods just use the scanned master model data without using the CBCT scan to build the mucosa model. In this method technician modify the master cast by trimming 2mm plaster to simulate the bone. Though it can reveal the qualities of mucosa, but still the uniform 2 mm thickness could not provide the exact thickness of oral mucosa and precise morphology of the alveolar bone. Dissimilar to the previously described methods, the present article postulated a newer method of determining the detailed features of oral mucosa and bone. By appropriately adjusting the CBCT scan and scanned data of master model the more precise mucosal model, was generated for analysing the mechanical behaviors of mucosal supported RPD with three-dimensional FEA.

Limitations-

The stresses over the mucosa, bone and on framework of RPD were assessed in the present study with the help of FE model which was fabricated with masking and NURBS method to depict clinical situation but still it is not completely possible to generalize the data for a clinical scenarios because of inherent the limitations of FEA models. Material properties were applied which were based on standard average values specific to each material, although the linear static analysis was performed but the structures were considered isotropic, homogeneous and linearly elastic which are vital anisotropic tissues. (12). Loading force applied were straight, obliques and static but it cannot be assumed correct during chewing in normal oral conditions where vector of forces are generated and dynamic. Finally study was based on mathematical model so it is recommended to correlate its results with in-vivo study.

However, there are also several limitations with this study. In this study we only enrolled one patient with one type of edentulous arches (Kennedy Class I). More types of edentulous arches with more cases are needed to give a much stronger point. What is more, our patient has a prolonged history of tooth loss, which caused severe alveolar bone resorption that led to a reduction of PDL area. The smaller area of PDL may cause more significant stress concentration in PDL and displacement of the teeth. Moreover, the anatomical shape of the roots was not satisfyingly proper, which may be explained by the not so significant difference of contrast between the root and cancellous bone in the CBCT data.

Conclusions

Within the limitation of the study, it can be concluded that the framework made of PEEK has more stress on the mucosa under lying the distal extension RPD and the dislodgment of the free end saddle of the PEEK framework is greater, which is a drawback for the stability of the RPD and may cause pain and resorption in mucosa and alveolar bone respectively.

Acknowledgements

The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through Research Group Project under grant number (R.G.P.1/122/40).

References

1. Lin, D., Li, Q., Li, W. & Swain, M. Dental implant induced bone remodeling and associated algorithms. J. Mech. Behav. Biomed.Mater. 2, 410–432 (2009).
2. Wills, D. J. &Manderson, R. D. Biomechanical Aspects of Support of Partial Dentures. J. Dent. 5, 310–318 (1977).
3. Monteith, B. D. Management of Loading Forces on Mandibular Distal-Extension Prostheses .1. Evaluation of Concepts for Design. J. Prosthet. Dent. 52, 673–681 (1984).
4. Green LK,Hondrum SO: The effect of design modifications on the torsional and compressive rigidity of U-shaped palatal major connectors. J Prosthet Dent 2003;89:400-407
5. Ben-Ur Z, Mijiritsky E, Gorfil C, et al: Stiffness of differentdesigns and cross-sections of maxillary and mandibular major connectors of removable partial dentures. J Prosthet Dent 1999;81:526-532
6. Barbenel JC: Design of partial denture components. I. Middle palatal bars. J Dent Res 1971;50:586-589
7. Becker CM, Kaiser DA, Goldfogel MH: Evolution of removable partial denture design. J Prosthodont1994; 3:158-166.
8. Schwitalla AD, Spintig T, Kallage I, et al: Flexural behavior of PEEK materials for dental application. Dent Mater 2015;31:1377-1384
9. Wiesli MG, Ozcan M: High-performance polymers and their potential application as medical and oral implant materials: a review. Implant Dent 2015;24:448-457
10. Tannous, F., Steiner, M., Shahin, R. & Kern, M. Retentive forces and fatigue resistance of thermoplastic resin clasps. Dent. Mater. 28,273–278 (2012).
11. Bathala, L., Majeti, V., Rachuri, N., Singh, N. &Gedela, S. The Role of Polyether Ether Ketone (Peek) in Dentistry - A Review. J. Med. Life. 12, 5–9 (2019).
12. Zoidis P, Papathanasiou I, Polyzois G: The use of a modified poly-etherether-ketone (PEEK) as an alternative framework material for removable dental prostheses. A clinical report. J Prosthodont2016;25:580-584
13. Pacurar M, Bechir ES, Suciu M, et al: The benefits of polyether-ether-ketone polymers in partial edentulous patients. Mater Plast2016;3:657-660
14. Muhsin SA, Wood DJ, Johnson A, et al: Effects of novel polyetheretherketone (PEEK) clasp design on retentive force at different tooth undercuts. J Oral Dent Res 2018;5:13-25
15. Dogru, S. C., Cansiz, E. & Arslan, Y. Z. A Review of Finite Element Applications in Oral and Maxillofacial Biomechanics. J. Mech. Med. Biol. 18 (2018).
16. Reddy, J. N. An introduction to the finite element method. (New York, 1993).
17. Schwitalla, A. D., Abou-Emara, M., Spintig, T., Lackmann, J. & Mueller, W. D. Finite element analysis of the biomechanical effects of PEEK dental implants on the peri-implant bone. J. Biomech. 48, 1–7 (2015).
18. Zelic, K. et al. Mechanical weakening of devitalized teeth: three-dimensional Finite Element Analysis and prediction of tooth fracture. Int. Endod. J. 48, 850–863 (2015).
19. Tanasic, I., Milic-Lemic, A., Tihacek-Sojic, L., Stancic, I. & Mitrovic, N. Analysis of the compressive strain below the removable and fixed prosthesis in the posterior mandible using a digital image correlation method. Biomech. Model. Mechanobiol. 11, 751–758 (2012).
20. Xiao, W. et al. Influence of connection type on the biomechanical behavior of distal extension mandibular removable partial dentures supported by implants and natural teeth. Comput. Methods Biomech. Biomed. Engin. 19, 240–247 (2016).

21. Suenaga, H. et al. Mechanobiological Bone Reaction Quantified by Positron Emission Tomography. J. Dent. Res. 94, 738–744 (2015).
22. Van Noort, R. & Physics Dental biomechanics-Edited by Arturo N. Natali (multiple author contribution). Medical Engineering Physics. 10, 893–894 (2003).
23. Bibb, R. Woodhead Publishing Series in Biomaterials. J Advances in Polyurethane Biomaterials (2016).
24. Shahmiri, R., Aarts, J. M., Bennani, V., Atieh, M. A. & Swain, M. V. Finite Element Analysis of an Implant-Assisted Removable Partial Denture. Journal of Prosthodontics-Implant Esthetic and Reconstructive Dentistry. 22, 550–555 (2013).
25. Wei, J., Xu, B.-T., Li, Q. & Wang, Y.-N. Three-dimensional finite element analysis of removable partial denture with periodontally compromised abutments. Zhonghuakouqiangyixue za zhi = Zhonghuakouqiangyixuezazhi = Chinese journal of stomatology. 48,409–413 (2013).
26. Li, W., Li, Q., Steven, G. P. &Xie, Y. M. An evolutionary approach to elastic contact optimization of frame structures. Finite Elements in Analysis and Design. 40, 61–81 (2003).
27. Viecilli, R. F., Katona, T. R., Chen, J., Hartsfield, J. K. Jr. & Roberts, W. E. Three-dimensional mechanical environment of orthodontic tooth movement and root resorption. Am. J. Orthod. Dentofacial Orthop 133 (2008).
28. Bourauel, C. et al. Simulation of orthodontic tooth movements. A comparison of numerical models. Journal of orofacial orthopedics = Fortschritte der Kieferorthopadie: Organ/official journal Deutsche Gesellschaft fur Kieferorthopadie. 60, 136–151 (1999).
29. Penedo, N. D., Elias, C. N., Pacheco, M. C. T. &Gouvêa, J. P. 3D simulation of orthodontic tooth movement. 15, 98–108 (2010).
30. Ortiz-Puigpelat, O. et al. Influence of Implant Position in Implant-Assisted Removable Partial Denture: A Three-Dimensional Finite Element Analysis. Journal of Prosthodontics-Implant Esthetic and Reconstructive Dentistry. 28, E675–E681 (2019).
31. Geramy, A. &Sharafoddin, F. Abfraction: 3D analysis by means of the finite element method. Quintessence Int. 34, 526–533 (2003).
32. Harb, I. E., Abdel-Khalek, E. A. &Hegazy, S. A. CAD/CAM Constructed Poly(etheretherketone) (PEEK) Framework of Kennedy Class I Removable Partial Denture: A Clinical Report. Journal of Prosthodontics-Implant Esthetic and Reconstructive Dentistry. 28, E595–E598 (2019).
33. Wada, S., Wakabayashi, N., Tanaka, T. &Ohyama, T. Influence of abutment selection in maxillary Kennedy Class II RPD on elastic stress distribution in oral mucosa: an FEM study. Journal of prosthodontics: official journal of the American College of Prosthodontists.15, 89–94 (2006).
34. Ohguri, T., Kawano, F., Ichikawa, T. & Matsumoto, N. Influence of occlusal scheme on the pressure distribution under a complete denture. Int. J. Prosthodont. 12, 353–358 (1999).
35. Roedema, W. H. Relationship between Width of Occlusal Table and Pressures under Dentures during Function. J. Prosthet. Dent. 36,24–34 (1976).
36. Inoue, S., Kawano, F., Nagao, K. & Matsumoto, N. An in vitro study of the influence of occlusal scheme on the pressure distribution of complete denture supporting tissues. Int. J. Prosthodont. 9, 179–187 (1996).
37. Zmudzki, J., Chladek, G. &Kasperski, J. The influence of a complete lower denture destabilization on the pressure of the mucous. membrane foundation. Acta of Bioengineering and Biomechanics. 14, 67–73 (2012).
38. Mori, S., Sato, T., Hara, T., Nakashima, K. &Minagi, S. Effect of continuous pressure on histopathological changes in denture supporting tissues. J. Oral Rehabil. 24, 37–46 (1997).
39. Tanaka, M., Ogimoto, T., Koyano, K. & Ogawa, T. Denture wearing and strong bite force reduce pressure pain threshold of edentulous oral mucosa. J. Oral Rehabil. 31, 873–878 (2004).
40. Ogawa, T. et al. Mapping, profiling and clustering of pressure pain threshold (PPT) in edentulous oral mucosa. J. Dent. 32, 219–228(2004).

41. Wei, J., Xu, B.-T., Li, Q. & Wang, Y.-N. Three-dimensional finite element analysis of removable partial denture with periodontally compromised abutments. Zhonghuakouqiangyixue za zhi = Zhonghuakouqiangyixuezazhi = Chinese journal of stomatology. 48,409–413 (2013).
42. Ahmad, R., Abu-Hassan, M. I., Li, Q. & Swain, M. V. Three dimensional quantification of mandibular bone remodeling using standard tessellation language registration based superimposition. Clin. Oral Implants Res. 24, 1273–1279 (2013).