Institution of MECHANICAL ENGINEERS
Journal of MECHANICAL ENGINEERING SCIENCE

Proc IMechE Part C:
J Mechanical Engineering Science
2022, Vol. 236(17) 9407–9418

DOI: 10.1177/09544062221096634
journals.sagepub.com/home/pic
SAGE

Finite element analysis of class II mandibular unilateral distal extension partial dentures

Laith A Sabri[1], Jwan F Abdulkareem[2], Kareem N Salloomi[3], Suza A Faraj[2], Abdulsalam R Al-Zahawi[4], Oday I Abdullah[5,6,7] and Ibrahim Tulunoglu[8]

Abstract
The current paper aims to investigate the stress distribution developed in Kennedy Class II mandibular distal extension removable partial dentures due to applying a unilateral load condition in both vertical and lateral oblique directions. 3D models of mandible bone and RPD framework were first built based on actual patient data and later exported to ANSYS software to implement the numerical analysis. For realistic analysis, the model considered the frictional contact between the RPD retainers with the teeth and mucosa with the resin denture base by applying the feature of small sliding. To ensure maximum longevity and suitability of restoration, two different metallic RPDs constructed from commercially pure titanium (CP Ti) and cobalt–chromium (Co-Cr) base materials were investigated within the proposed model. It was found that the highest stress value was seen within the Co-Cr framework followed by the titanium framework, particularly within the bar clasp under both loading directions. The principle abutment of the distal extension side carried the highest stress value under both RPD models in both loading cases. Also, it was found that the captured von Mises stress levels within the titanium bar clasps were lower than that in Co-Cr demonstrating both long durability and high flexibility of Ti clasps.

Keywords
Removable partial denture, unilateral distal extension base, finite element analysis, partially edentulous mandible

Introduction

The percentage use of removable partial dentures (RPDs) for rehabilitation of completely or partially edentulous adults has been reported to be increasing, leading to the high possibility of owning teeth when people get older[1]. As a consequence, there is a rapidly growing need for teeth replacements to restore both efficient function and social roles. Although there are potential risks of having an RPD such as the increase of plaque build up around the abutment teeth and bone loss at the areas of missing teeth, the benefits from using professionally developed designs of RPDs are many, including amended manifestation and self-assurance, easy crunching, improved speech, prevention of teeth moving and the ramification of lost teeth, reduction the risk of temporomandibular joint dysfunction, and prevention of facial changes. Based on these advantages, several types of RPDs are currently in use; all of these apply standard teeth as replacements for the missing natural teeth. The types of dentures are mainly differing in design parameters, which involve: shape design, materials, types of retainers, and type of support[2]. The difference in these parameters results in different biomechanical behavior of distal extension RPDs in addition to varying levels of induced stresses, which play an essential role in the success of this particular type of prosthesis. As a result, the service expectancy of an RPD will depend majorly on the degree of control of different stresses-induced throughout its structure.

As we stated above, one of the major differences between these RPDs is the material type used to support the denture teeth and retain the RPD in the mouth.[3] The suitable selection of the material type will keep the generated levels of stresses within certain limits allowing for the necessary maintenance of the supporting structures without risks. The accomplished research over the last two decades within the area of material type shows that metal and non-metal alloys might be an alternative to satisfy the purpose of decreasing

[1]Department of Mechatronics, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, Iraq
[2]Department of Prosthodontics, College of Dentistry, University of Sulaimani, Sulaimani, Iraq
[3]Automated Manufacturing Engineering Department, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad, Iraq
[4]Conservative Department, College of Dentistry, University of Sulaimani, Sulaimani, Iraq
[5]Department of Energy Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
[6]Department of Mechanics, Al-Farabi Kazakh National University, Kazakhstan
[7]System Technologies and Engineering Design Methodology, Hamburg University of Technology, Hamburg, Germany
[8]Department of Comprehensive Care, Case School of Dental Medicine, Case Western Reserve University, Cleveland, OH, USA

Corresponding author:
Laith A Sabri, Department of Mechatronics, Al-Khwarizmi College of Engineering, University of Baghdad, Baghdad 10011, Iraq.
Email: laith@kecbu.uobaghdad.edu.iq

stresses and preserving the health of abutment teeth and their supporting structures.[4–6] Chrome alloys were used because of their high modulus of elasticity compared to gold alloys, but it permits less flexibility during the placement of cast clasps. To overcome this problem, either a small cross-sectional form of the clasp and less depth of the retentive undercut has to be used for chrome alloy, or an alternative such as wrought wire is used because of its internal structure, that is, longitudinal structure as compared to the grain structure of cast alloy, which in turn allows for high flexibility.[7] Another favorite option is to use CP Ti and Titanium alloys. These alloys have been used to fabricate removable denture frameworks due to reasons such as superior biocompatibility, prominent corrosion strength, and mechanical toughness, which are analogous to those properties of gold alloy.[8] In actual situations, different types of stress might be generated due to improper framework design and inaccurate sizing, and these stresses may cause impingement of the gingival structure or twist the abutment. Also, the distribution of the applied forces on the abutment teeth and residual ridge to the underlying supporting structures are essential considerations when designing and constructing RPDs. The load exerted on an RPD, particularly in Kennedy class I or II RPDs is rationed between the abutment teeth and the residual ridges[9]. Therefore, an adequate understanding of the stresses generated by both RPDs and external applied forces represents a necessity to satisfy the maximum longevity and suitability of a restoration.

Due to the high complexity involved in modeling structures such as mandibular unilateral distal extension RPDs, most of the former research studies that deal with the prediction of stress levels encountered during load application were done using experimental methods such as photoelastic stress analysis, holography, and strain gauge.[10–14] The experimental methods showed that direct experimental measurement of stress distribution at some critical locations in the complex geometries is difficult. However, advances in computer modeling methods supply an alternative choice to realistically predict stress profiles. Quantitative methods like the finite element method (FEA) are a well-accepted theoretical alternative for computing stress distribution within complex geometries.[15–17] This method gave acceptable results in the case of investigating the effect of changing model design parameters of RPDs on the stress levels or biomechanical behavior of mandible Kennedy class I RPDs.[18,19] In addition, the FEA has been applied efficiently to evaluate the stresses generated in the case of implant-assisted distal extension RPDs.[20–24] To cover up the effect of using different material types, the FEA has been used to investigate the stress distribution in tooth-supported RPDs made of Co-Cr and thermoplastic nylon.[25]

The present study aims to design a 3D FE model from actual patient data using a combination of computed tomography (CT) scan equipment and computer-aided design (CAD) software to assess the stress distribution under mandibular class II distal extension RPDs constructed from CP Ti and Co-Cr alloys. Most of the previous studies used either a simplified finite element model in which the primary model parts such as tissue, cortical bone, and spongy bone were not considered in the simulation study, or the study did not consider the effect of using different RPD materials on stress distribution, and its consequences on issues like longevity and suitability of a restoration.[23,25,26] Unlike the previous studies, this study investigates the stress pattern in both the RPD framework and the underlying supporting structures (mandibular bone, supporting mucosa, and principle abutment teeth). In addition, the current proposed model considers the feature of the actual contact between the various parts of the evaluated designs. The actual contact was not considered by most of the previous literature and instead, it was assumed to be rigid contact.

Materials and methods

The geometry of the components of the 3D finite element model of a Kennedy Class II classification edentulous mandible restored with two different RPDs fabricated of a CP Ti and a Co-Cr alloy were created using CAD modeling software, followed by a process of assembly of the individual parts, and form the global structure. The steps of constructing the 3D model geometry were similar to those described in previous publications.[15,17,23,26,27,28] To do so, a computerized image model of a class II modification 1 partially edentulous mandible was made by using the CT scan data of a female patient after obtaining patient consent. Based on image density thresholding, different hard and soft tissues have been identified. Furthermore, the features of thresholding and segmentation were applied to separate the spongy bone from the compact alveolar bone and to separate the principle abutment teeth: the left 2nd premolar, right 2nd premolar, and 2nd molar. For the construction, a 2 mm layer thickness of the supporting mucosal layer was constructed overall mandible model and around the remaining teeth to replicate the supporting mucosal tissue. To further satisfy realistic simulation, a periodontal ligament (PDL) layer of 0.2 mm thickness was incorporated around the roots.

Concerning RPD models, two RPD metal frameworks were constructed for the same female volunteer, with the same design but different base materials (CP Ti and Co-Cr). As we explained earlier, the selected case was for Kennedy class II modification 1 with three missing teeth: first, second and third molars in the edentulous distal extension at the left side and the first molar at the modification are at the right side. The following design was used: lingual plate major connector, RPI clasp assembly (bar clasp, mesial occlusal rest, distal proximal plate) on the second premolar of the distal extension side, circumferential clasps on the second premolar and second molar of the modification side, and acrylic resin artificial teeth replaced the missing natural teeth. In order to create the 3D RPD metal framework model, a CT scan was taken for the RPD metal framework, and subsequent construction was undertaken using the same steps as for 3D mandible model construction.[15,16,23,26] Later, the 3D model of the metallic RPD framework was adapted over the previously created 3D mandible model in addition to build up the acrylic denture base part with the required artificial teeth on the metal frame part. All the constructed model parts were then imported into SolidWorks software and exported as a solid 3D model in SAT file format.[15,17,23]

To start the FEA, the assembly of all model parts that included the partially edentulous mandible bone, supporting mucosa and RPD were imported into ANSYS Workbench software, as shown in Figure 1. The simulation options available within ANSYS simulator were used to define the material properties, mesh the model, apply boundary conditions, load the model, and finally implement the analysis. The interactions between the individual parts of the 3D model were applied through defining the contact behavior. The feature of perfectly bonded surfaces was used to simulate the contact between the periodontal ligament (PDL) and teeth, mandible bone and PDL, mandible bone and soft tissue, left and right resin denture bases with the RPD metal. Alternatively, frictional contact behavior was used to model the contact between the other geometry parts. A friction coefficient of 0.1 was applied to model the contact between the occlusal rest direct retainer and the teeth, while a friction coefficient value of 0.01 was utilized for the contact surface between the resin denture base and the soft tissue.[23]

All the materials were assumed to be homogeneous, linear, and have elastic material behavior characterized by the two material constants of Young's modulus and Poisson's ratio. The elastic properties of the materials used in the models were taken from previous studies as shown in Table 1.[22,29,30,31] To prevent displacement and rotation of the model during force application on the occlusal surface of the RPD (i.e., zero displacement constraints), the volume of the upper section of the ramus and two-thirds of the inferior border starting from the anterior angle of the mandible were assumed to be fixed in all directions (anterio-posterior, medio-lateral, and superior-inferior). For meshing purposes, the ten-node tetrahedral type of element which is recommended for complex geometries was used to mesh the models,[15,23] as shown in Figure 2. A number of 394,303 total elements and 682,081 nodes were used to mesh the whole model. The element mesh size used was ranging between 0.35 and 3.5 mm depending on the region geometry and volume.

The stress analysis was conducted with a unilateral loading condition of 101.57 N distributed on the occlusal surface of the artificial left first and second M in the distal extension side. The load of 101.57 N was calculated according to a pilot study performed on 10 patients provided with Kennedy Class II modification 1 metallic RPDs (CP Ti and Co-Cr. The pilot study involved a sample of 10 cases of Kennedy Class II lower partially edentulous patients with posterior modification (all-female aged 50–60 years old) and provided with two different types of unilateral distal extension RPD including artificial first and second molar in free end side and the missing teeth in the modification side. The upper arch was natural dentition with no artificial appliance or missing posterior teeth. The patients were selected according to clinical criteria. The maximum bite force (MBF) was measured unilaterally in the distal extension side for each patient with each type of RPD using a portable type of occlusal force gauge. The mean of all MBF values given by all the patients was calculated and used as a maximum load to be applied in the present study.

The loading of the dentures was performed in two directions, vertical and lateral oblique at a 45° angle to the long axis of the tooth, and at the central fossa of the artificial teeth, as shown in Figure 3. After load application, a linear elastic analysis was performed for each loading direction by

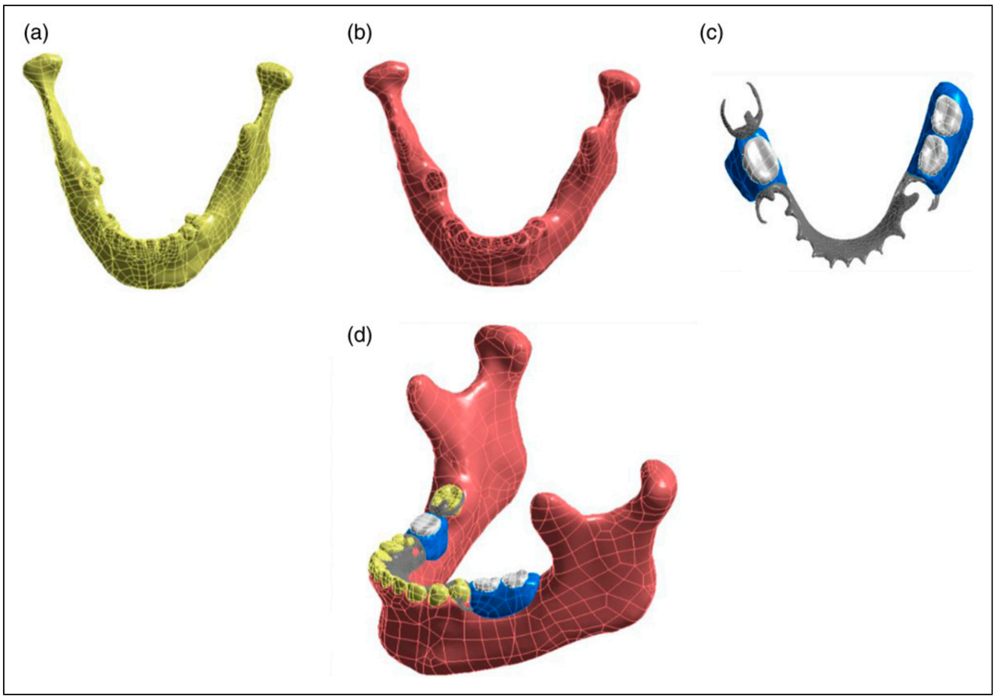

Figure 1. Assembly of 3D model parts into ANSYS program; A- Partially edentulous mandible bone, B- supporting mucosa, C- Metallic RPD (Co-Cr and Titanium), D- partially edentulous mandible replaced with Co-Cr and Titanium RPDs.

Table 1. Young's modulus and Poisson's ratios applied in the FEA.

Materials	Young's modulus (MPA)	Poisson's ratio	References
Enamel	84,000	0.30	22,28
Dentine	18.300	0.30	22,28
Periodontal ligament	68.9	0.45	22,28
Spongy bone	1370	0.30	22,28
Cortical bone	13,700	0.30	22,28
Mucosa	19.6	0.37	22,28
Acrylic resin denture base	2650	0.35	22,28
Cobalt chromium	218,000	0.33	29,30
Commercially pure titanium	**103,000**	**0.34**	29,30

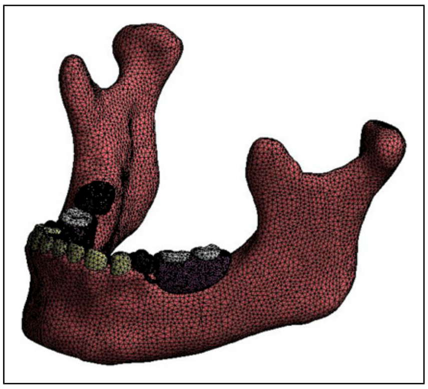

Figure 2. Mesh generation of the 3D FEA model.

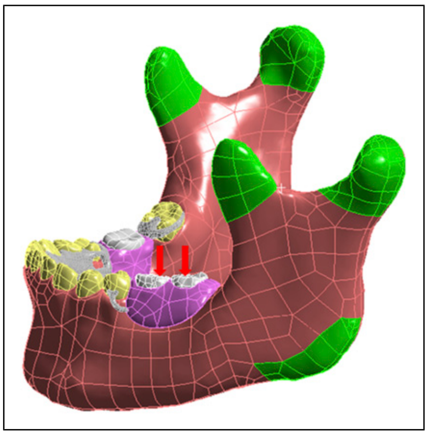

Figure 3. Loading pattern (red arrows) and boundary conditions (green regions).

means of the ANSYS workbench software, which was run on a high-performance personal computer, and stress analysis for each model was obtained. Quantities such as von Mises stress (equivalent tensile stress), minimum principal, and maximum principal are used to predict the effect of loading forces on the RPD models or the prosthesis structure.

Results

Maximum von Mises stresses in the RPD and its underlying supporting structures (mandibular bone, supporting mucosa, and principle abutment teeth) were calculated and evaluated in both RPD models under two loading directions to show the criticality and disposition to collapse of the considered structures. The stress contours for the whole structure considered in this study are shown in Figure 4.

For the case of the vertical unilateral loading condition, the distribution of the resulting von Mises stress of the two RPD models is shown in Figure 5. It is clear that the highest level of von Mises stress (479.27 MPa) was deducted in the Co-Cr RPD framework, followed by Ti RPD (416.03 MPa). In both Co-Cr and Ti RPD models, the maximum stress areas appeared within the bar clasp. For both models, the von Mises stress values in principle abutment of the distal extension side (left 2nd premolar) and its PDL were higher than the stress values in the abutments of (right 2nd premolar and right 2nd molar) and their PDL. The highest stress on the abutments was produced by the Co-Cr RPD model followed by the Ti RPD, with a difference of 49 MPa in stress values of the two cases. In all models, the maximum stress concentration location in the right 2nd premolar appeared within the enamel portion in the distal side of the crown, while the maximum stress concentration area in the associated PDL appeared in the region down the coronal part of the PDL as shown in Figure 6.

Considering the underlying bone and supporting mucosa, higher von Mises stress appeared in the cortical bone as compared to spongy bone and supporting mucosa under the two RPD models. More specifically, maximum stress concentration in the cortical and spongy bone under both Co-Cr and titanium RPDs appeared in the buccal shelf area. Concerning supporting mucosa, the same stress pattern was recorded in both Co-Cr and Titanium RPD models and the maximum stress area appeared in the distobuccal part of the distal extension side of the ridge. The distribution of the equivalent von Mises stress in the cortical bone, spongy bone, and the supporting mucosa of the two RPD models under the vertical unilateral loading condition are shown in Figures 7–9.

For the case of the unilateral lateral oblique (LO) loading condition, Figure 10 shows the maximum von Mises stress values in different parts of the two RPD models and their distribution. The stress values are slightly less than the case of vertical loading in which a higher stress value was indicated in the case of the Co- Cr RPD framework (353.56 MPa), followed by the Ti RPD (286.1 MPa). The

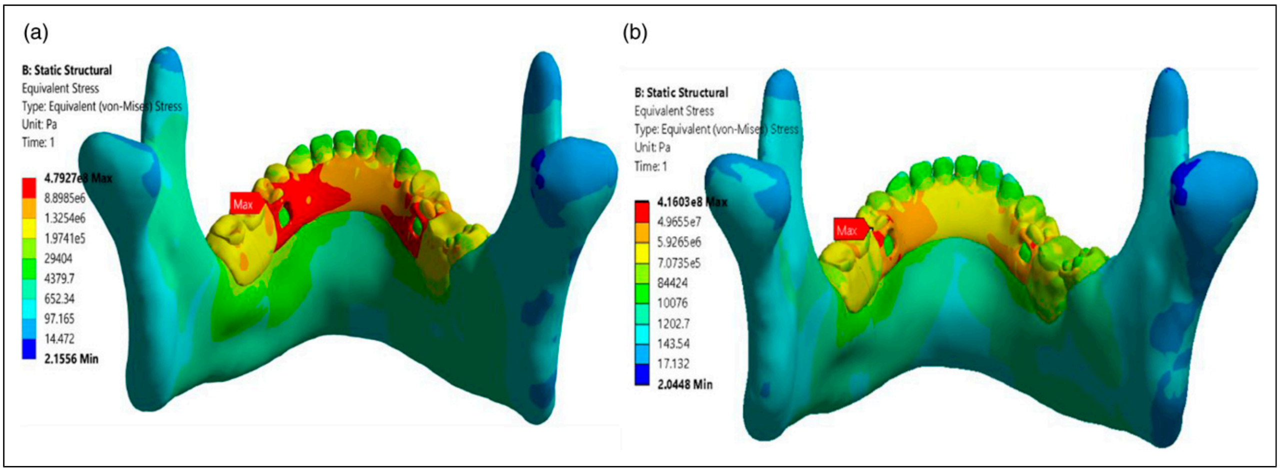

Figure 4. Distribution of equivalent von Mises stress pattern under the application of unilateral vertical load in A: Co-Cr RPD model, B: Ti RPD model.

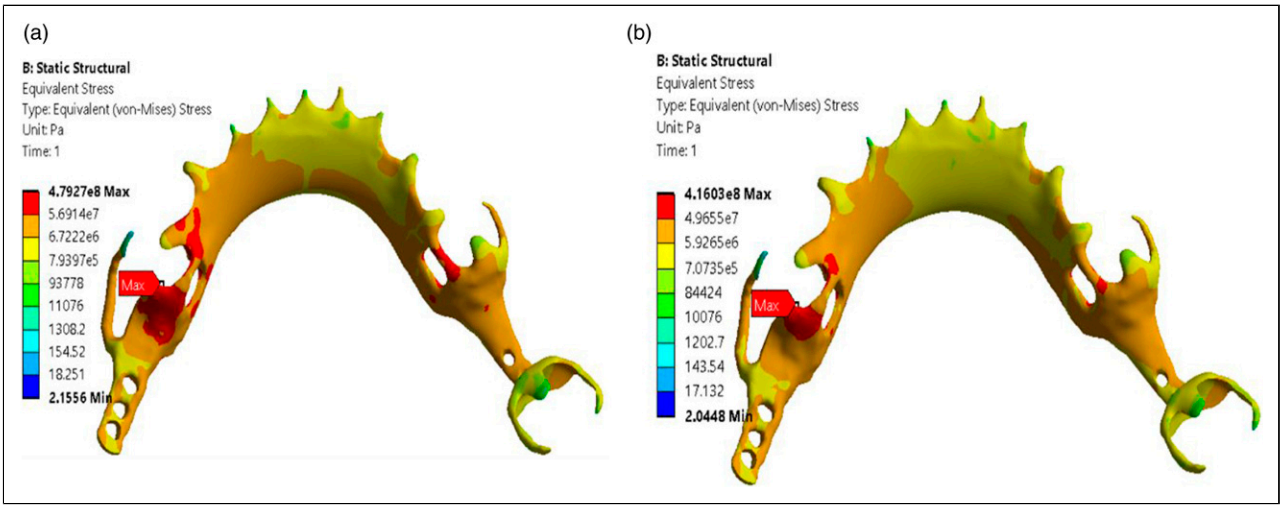

Figure 5. Distribution of maximum von Mises stress in different RPD frameworks under vertical unilateral loading condition; A: Co-Cr RPD model, B: Ti RPD model.

location of maximum stress concentration observed in the two RPD frameworks under LO loading conditions was similar to that observed under vertical loading conditions, Figures 11 and 12.

For the underlying supporting structures, slightly higher stress values were recorded under the LO loading direction as compared to vertical loading, particularly in the underlying cortical bone. Moreover, localization of maximum von Mises stress distribution in the principle abutments, spongy bone, and supporting mucosa were the same as that seen under the vertical load application in the two models, as shown in Figures 12–14. The maximum stress concentration area in the PDL was in the region down the coronal part of the PDL, lingually in relation to the associated abutment. In the supporting mucosa layer, the localization of maximum stress concentration in the two models was around the socket of the left 2nd premolar, as indicated by Figure 15

Table 2 summarizes the maximum von Mises stresses encountered during simulation using two different RPD frameworks under both unilateral vertical and lateral oblique loading conditions for all the geometry components considered in this study.

Discussions

Using distal extension RPDs as an alternative option for the rehabilitation of prosthesis needs special care and periodical maintenance due to common problems like lack of stability, minimal retention, un-esthetic retentive clasping, and discomfort upon loading.[21] The stresses generated due to such problems may accelerate failure or even collapse of the denture and its abutment leading to warping of the base. Therefore, analyzing the stress distribution within distal extension RPDs represents a necessity to examine the various attachment systems being used and the stresses that are transmitted to the whole structure. The current study used the finite element method to quantify numerically the values of the von Mises stress produced in different areas of lower class II mandibular

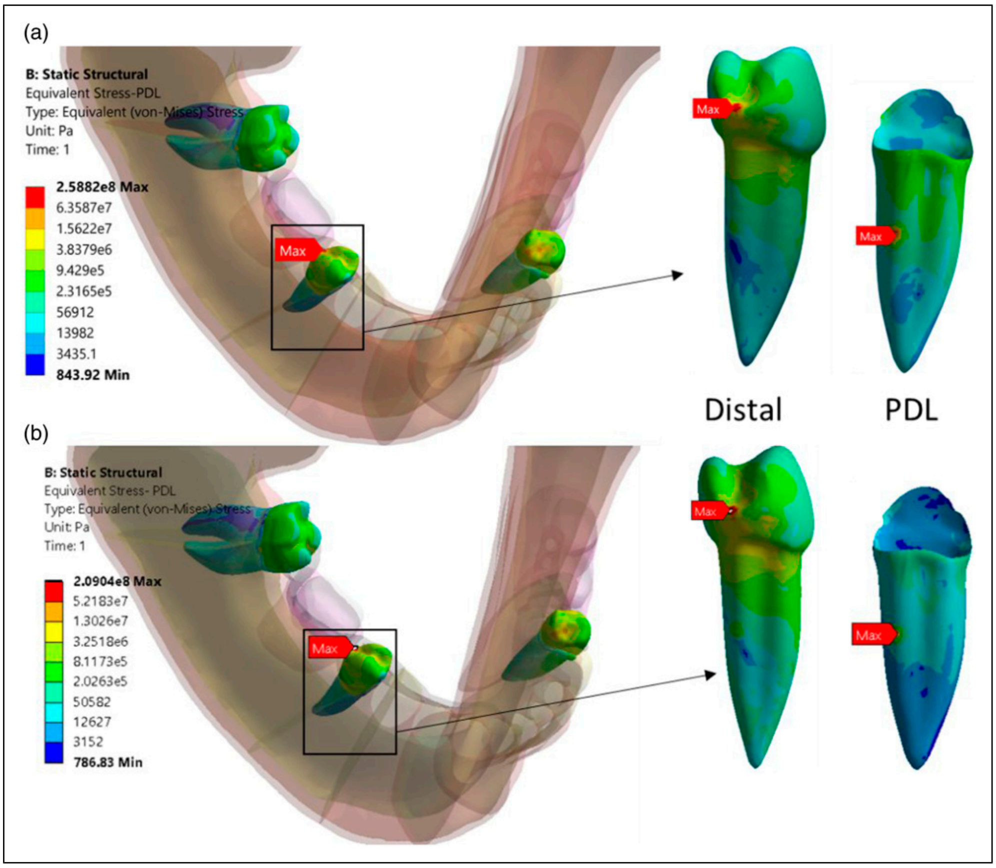

Figure 6. Distribution of maximum von Mises stress in principle abutment teeth and the associated PDL in different models under unilateral vertical loading condition; A: Co-Cr RPD model, B: Ti RPD model.

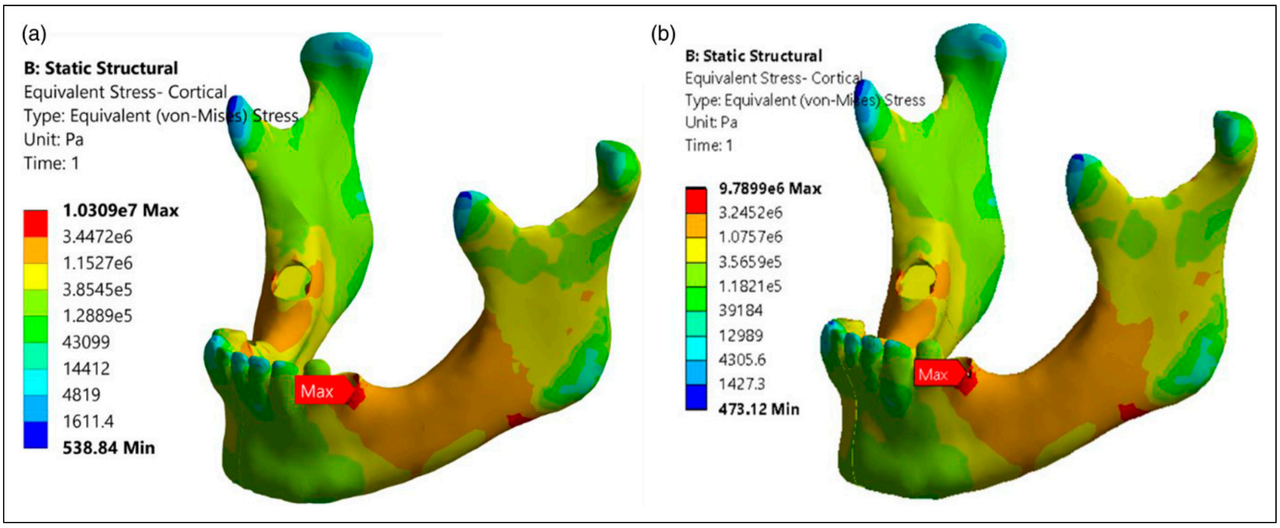

Figure 7. Distribution of maximum von Mises stress in cortical bone in different models under unilateral vertical loading condition; A: Co-Cr RPD model, B: Ti RPD model.

distal extension RPDs using two different metallic RPDs constructed from CP Ti and Co-Cr base materials. The stress was analyzed in this study under a unilateral load that assumed mastication in both vertical and lateral oblique directions.

The results of the FEA showed that in both loading directions the highest von Mises stress appeared in the Co-Cr RPD framework as compared to the Titanium RPD. This could be explained through the stiffness and rigidity of Co-Cr material that enables it to bear most of the exerted masticatory force. Lower levels of stress were found in the Ti RPD framework as compared to the Co-Cr RPD framework. This finding is consistent with that of Park et al.,[30] as they found the lowest von Mises stress values in CP Ti clasp when compared to a Co-Cr clasp. CP Ti has higher resiliency than Co-Cr alloy, and that approximates its

Table 2. Equivalent von Mises stress (MPa) in RPD appliance, principle abutment teeth, mandible bone, and mucosa during application of vertical and lateral oblique load in both RPD models.

Stress of two RPD models (Mpa)		Appliance	Principle abutments			Mandible bone		Mucosa
			Left premolar	Right premolar	Right molar	Cortical	Spongy	
Co/Cr RPD	Vertical load	479.27	84.95	285.82	6.97	10.30	1.69	0.69
	Lateral oblique load	353.56	89.40	256.63	11.31	22.58	1.93	0.88
Ti RPD	Vertical load	416.03	69.45	209.04	5.93	9.78	1.42	0.73
	Lateral oblique load	286.1	84.90	204.75	7.82	22.26	1.94	0.99

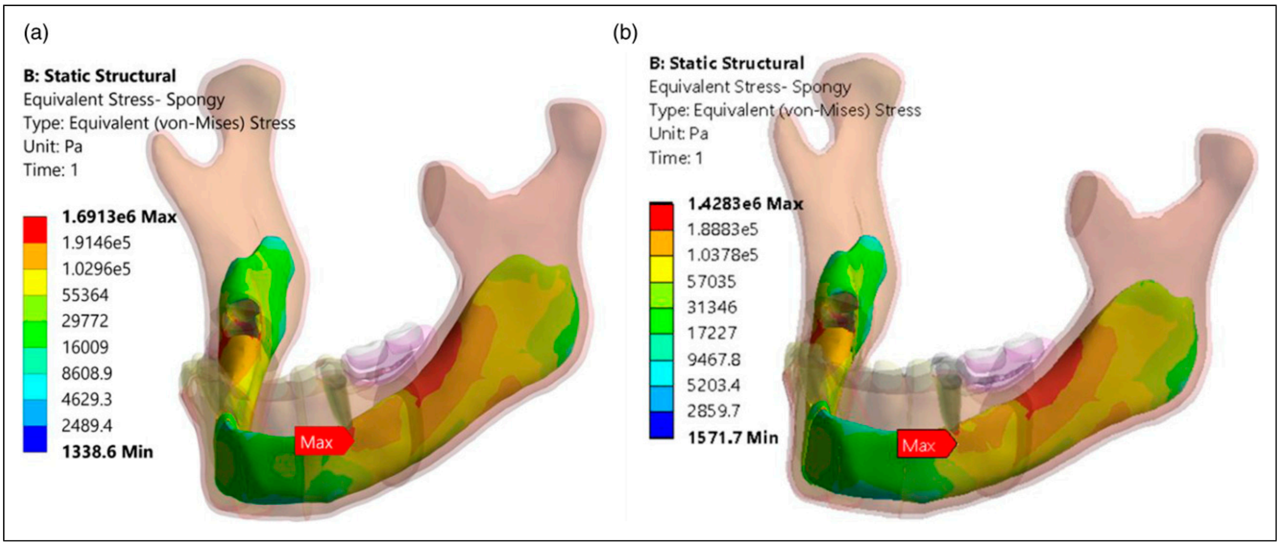

Figure 8. Distribution of maximum von Mises stress in spongy bone in different models unilateral vertical loading condition; A: Co-Cr RPD model, B: Ti RPD model.

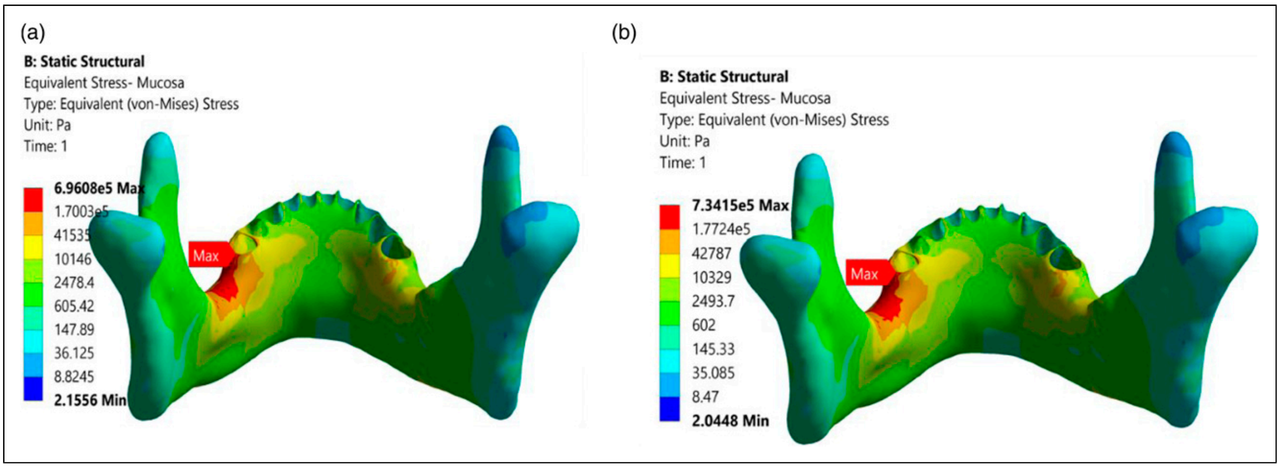

Figure 9. Distribution of maximum von Mises stress in supporting mucosa in different models under unilateral vertical loading condition; A: Co-Cr RPD model, B: Ti RPD model.

behavior to that of gold alloys. This property would allow the retentive clasp arms of RPDs to be placed in deeper undercuts on abutments than is possible with Co-Cr. Therefore, Titanium and Titanium alloys, despite the evidence of casting defects, are more suitable materials for the fabrication of clasps for RPDs, especially for situations involving deep undercuts. This characteristic is also useful in clinical conditions where esthetics or periodontal health is of essential interest.[4,31] Regardless of the value of the stress, the location of maximum stress concentration in both Co-Cr and Ti RPDs was within the bar clasp. This is possibly related to the design configuration of the bar clasp with limited surface area and mechanically this area represents an area of combined stress, tension, and bending. Higher von Mises

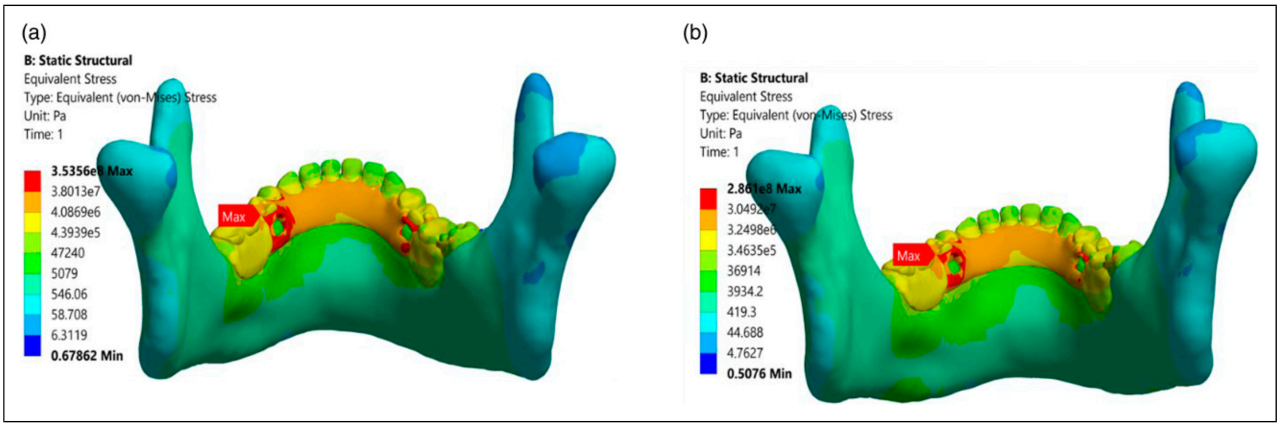

Figure 10. Distribution of equivalent von Mises stress pattern under the application of unilateral lateral oblique load in A: Co-Cr RPD model, B: Ti RPD model.

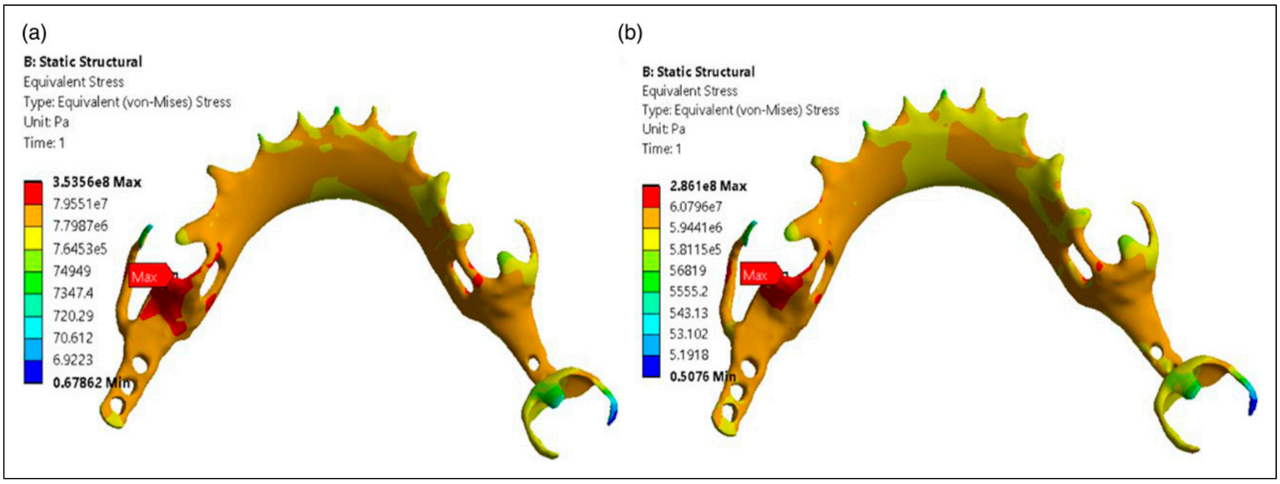

Figure 11. Distribution of maximum von Mises stress in different RPD frameworks under unilateral lateral oblique loading condition; A: Co-Cr RPD model, B: Ti RPD model.

stress appeared in cortical bone than spongy bone under both RPDs in both loading directions. This is due to the difference in the biological and mechanical characteristics of these two types of bone: the cortical bone is a dense bone with elastic modulus which is about 10 times that of the spongy bone and the cortical bone could, therefore, bear most of the loads transmitted from the occlusion. A similar finding was obtained by Gharechahi et al.[32,33].

The localization of stress in the underlying bone and supporting mucosa in both Co-Cr and Ti RPD models were located in the distal extension side, and this could be related to the unilateral load application in the present study. On the distal extension side of the model, the stress will be concentrated under the applied load especially in the vertical load direction. The terminal abutment of the distal extension side (right 2nd premolar) carried the highest stress value under both RPDs models in both loading directions. This can be explained by the rotational movement of the distal extension RPD around the fulcrum line passing through the most posterior abutments when forces are applied to the artificial teeth attached to the extension base. Differences in displaceability of the periodontal ligament of the supporting abutment teeth and soft tissue covering the residual ridge permit this rotation. Even though the actual movement of the denture may be small, a lever force may be imposed on terminal abutment teeth thus increasing the stress on the terminal abutment.[34] The results revealed that higher stress values appeared in the underlying bone and supporting mucosa under the lateral oblique load direction than under the vertical load. More particularly, in the cortical bone, the lateral component of force acted perpendicularly to the long axes of the supporting structures, bone, mucosa, tooth and PDL, yielding a combination of both compressive and tensile stresses in them. This finding is consistent with that of Wang et al.[35] who compared the effect of rigid and nonrigid exrtracoronal attachment in distal extension RPDs on the alveolar bone and abutment tooth PDL; they found that loading along the buccolingual direction had the greatest effect on the supporting structures. Here it is important to mention some of the current model limitations such as the model did not consider the viscoelastic behavior of parts like

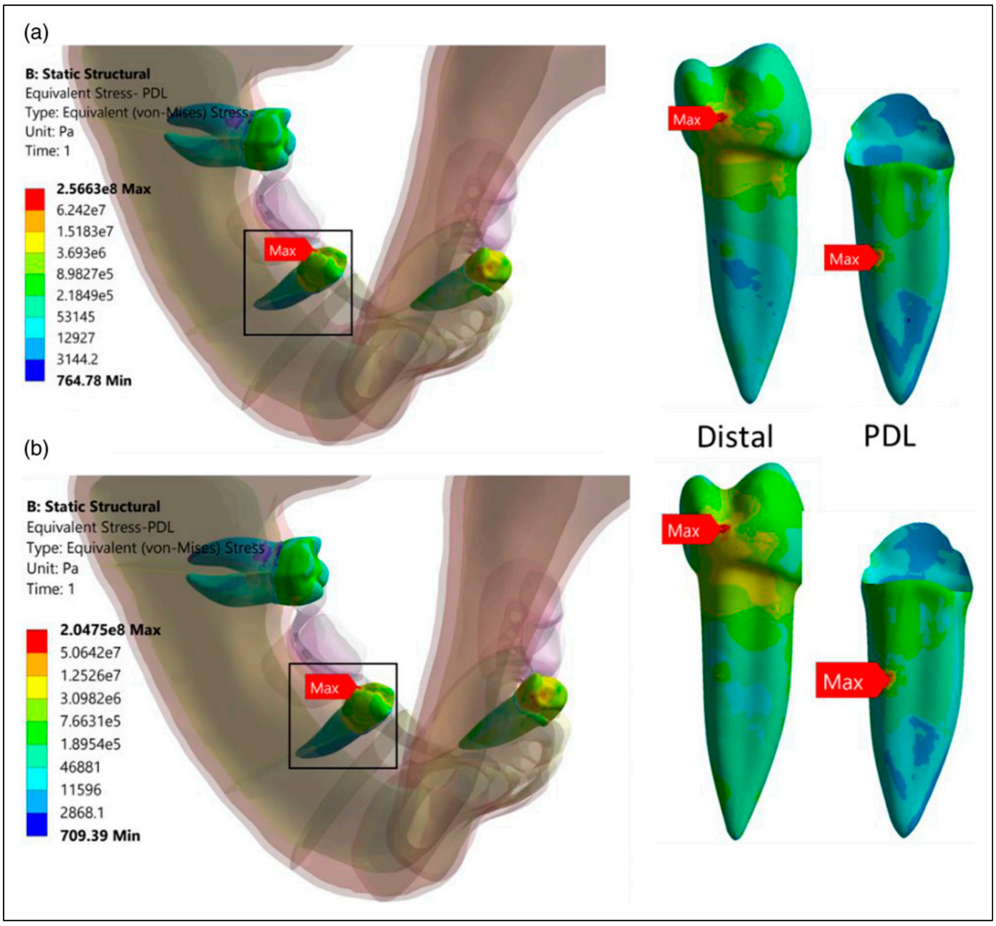

Figure 12. Distribution of maximum von Mises stress in principle abutment teeth and associated PDL in different models under unilateral lateral oblique loading condition; A: Co-Cr RPD model, B: Ti RPD model.

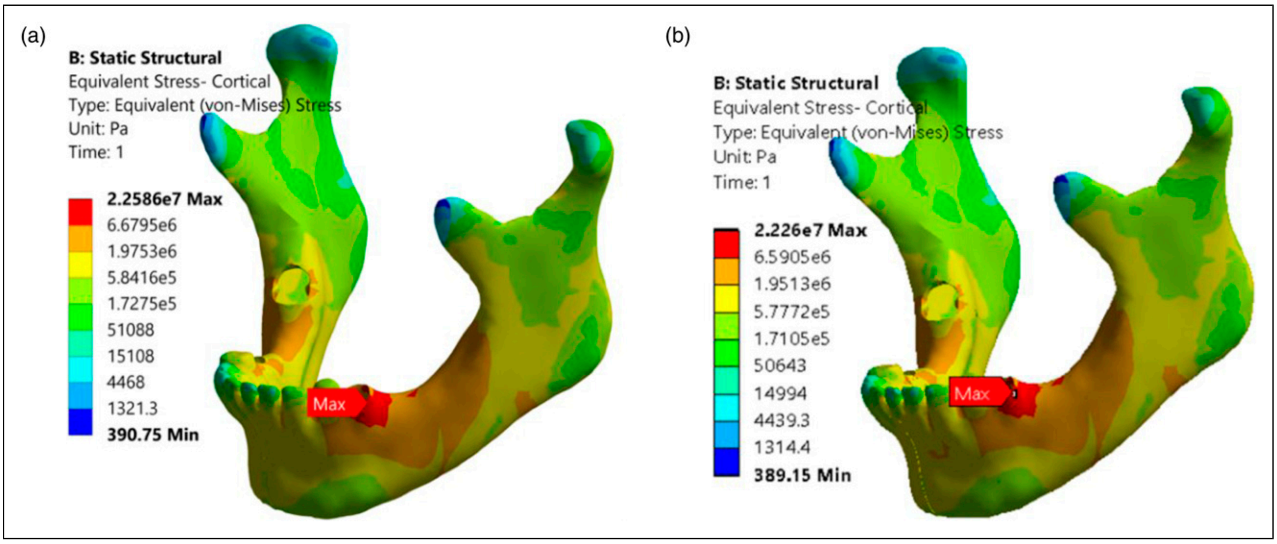

Figure 13. Distribution of maximum von Mises stress in cortical bone in different models under unilateral lateral oblique loading condition; A: Co-Cr RPD model, B: Ti RPD model.

Mucosa and instead it was assumed as an elastic body keeping in mind that the elastic behavior is adopted by previous literature. The same was used for the Enamel part which is an anisotropic material. The finite element can enhance its prediction for complex geometries such as the one analyzed here if precise material behavior was assigned, and accurate boundary conditions were applied.

In this work, the investigation of the mechanical stresses in the RPD and its underlying supporting structures, for both soft and hard structure, is very important in both

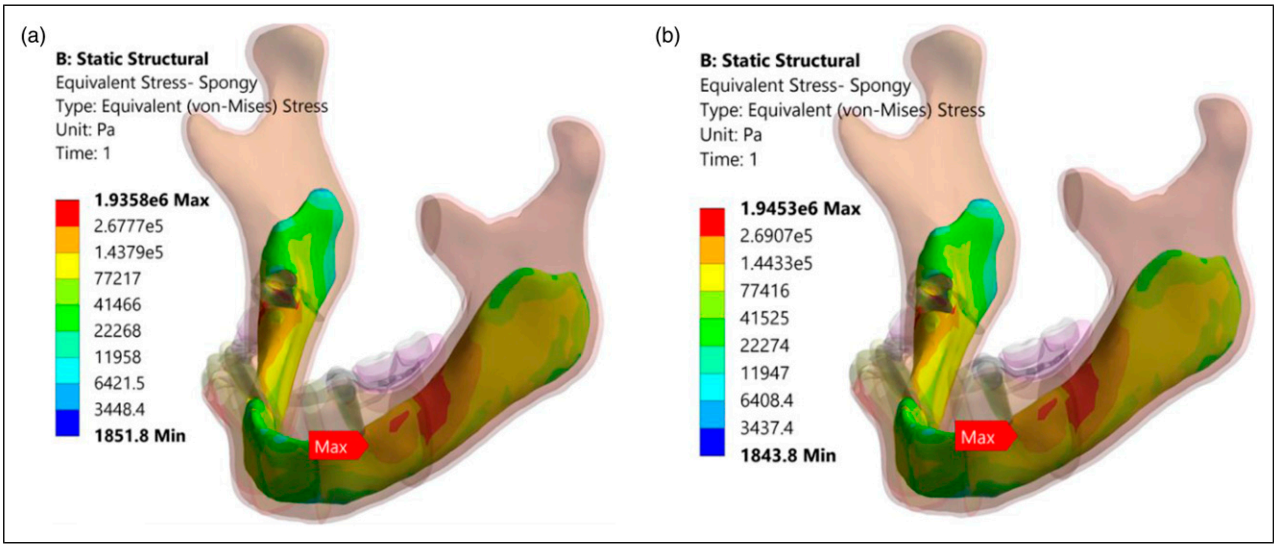

Figure 14. Distribution of maximum von Mises stress in spongy bone in different models under unilateral lateral oblique loading condition; A: Co-Cr RPD model, B: Ti RPD model.

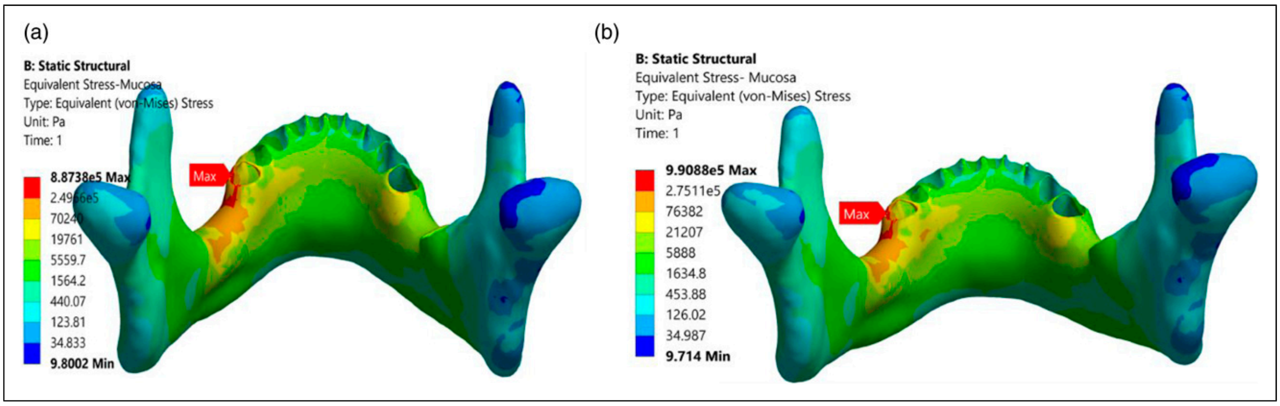

Figure 15. Distribution of maximum von Mises stress in supporting mucosa in different models under unilateral vertical loading condition; A: Co-Cr RPD model, B: Ti RPD model.

research and clinical practice, since understanding the effect of the RPD geometry and its material properties in mechanical stresses distribution and deformation values and shape will improve the design of RPD and should help in the prediction of the fracture location.

Conclusions

The following conclusions can be drawn from the present study:

- Finite element stress analysis showed lower levels of stress within Titanium bar clasps as compared to Co-Cr, indicating the longevity and suitability of Ti clasps.
- Higher stress appeared in cortical bone than spongy bone under both RPD models and the maximum stress concentration areas were noticed on the distal extension side.
- Lateral oblique load creates higher stress values in the underlying bone and supporting structures as compared to vertical load application.
- As future work, the authors recommend performing non-linear finite element analyses to simulate the viscoelastic properties of PDL and supporting mucosa. One more thing is studying the effect of different direct retainers and internal attachment designs on the stress distribution behavior of underlying supporting structures.

Declaration of Conflicting Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iD

Laith A Sabri https://orcid.org/0000-0003-4881-7186

References

1. Douglass CW and Watson AJ. Future needs for fixed and removable partial dentures in the United States. *J Prosthet Dent*, 2002; 87(1): 9–14.
2. Kim JJ. Revisiting the removable partial denture. *Dent Clin*. 2019; 63(2): 263–278. Doi: 10.1016/j.cden.2018.11.007
3. Wöstmann B, Budtz-Jørgensen E, Jepson N, et al. Indications for removable partial dentures: a literature review. *Int J Prosthod*.2005; 18(2): 139–145.
4. Bridgemana JT, Marker VA, Hummel SK, et al. Comparison of titanium and cobalt-chromium removable partial denture clasps. *J Prosthet Dent* 1997; 78(2): 187–193.
5. Souza JE, Silva NR, Coelho PG, et al. Retention strength of cobalt-chromium vs nickel-chromium titanium vs CP titanium in a cast framework association of removable partial overdenture. *J Contemp Dent Pract*. 2011; 12(3): 179–186.
6. Singh K, Aeran H, Kumar N, et al. Flexible thermoplastic denture base materials for aesthetical removable partial denture framework. *J Clin Diagn Res : J Clin Diagn Res*. 2013; 7(10): 2372–2373.
7. Arafa KAO Comparing the effects of titanium alloy and chrome cobalt in removable partial denture connectors on tooth mobility, bone loss and tissue reaction. *The Saudi Journal for Dental Research* 2016; 7: 112–117.
8. Ohkubo C, Hanatani S and Hosoi T. Present status of titanium removable dentures - a review of the literature*. *J Oral Rehabil* 2008; 35: 706–714.
9. Itoh H, Baba K, Aridome K, et al. Effect of direct retainer and major connector designs on RPD and abutment tooth movement dynamics. *J Oral Rehabil* 2008; 35: 810–815.
10. Lee HE, Wu JH, Wang CH, et al. Biomechanical analysis of distal extension removable partial dentures with different retainers. *J Dent Sci*. 2008; 3: 133–139.
11. Pellizzer EP, Ferraço R, Tonella BP, et al. Influence of ridge type on mandibular distal extension removable partial denture. *Acta Odontol Latinoam : AOL*. 2010; 23(1): 68–73.
12. Park C-W and Kay K-S. Photoelastic stress analysis of the mandibular unilateral free-end removable partial dentures according to the design. *The Journal of Korean Academy of Prosthodontics*. 2009;47(2):206-214.
13. Manumeet B, Jitender B, Gyanander A, et al. A review on stresses- induced by removable partial dntures. *International Journal of Contemporary Dentistry Medicine Rev*. 2015; 10: 1–5.
14. Campos JC, Correia A, Vaz MA, et al. Holographic stress analysis in a distal extension removable partial denture. *Eur J Prosthodont Restor Dent*. 2009; 17(3): 111–115.
15. Hussein FA, Salloomi KN, Abdulrahman BY, et al. Effect of thread depth and implant shape on stress distribution in anterior and posterior regions of mandible bone: A finite element analysis.*Dent Res J* 2019; 16: 200–207.
16. Sabri L, Hussein F, AL-Zahawi A, et al. Biomechanical finite element analysis of a single implant threaded in anterior and posterior regions of maxilla bone. *Indian J Dent Res* 2020; 31: 203–208
17. Dawood SN, Al-Zahawi AR and Sabri LA. Mechanical and thermal stress behavior of a conservative proposed veneer preparation design for restoring misaligned anterior teeth: A 3D finite element analysis. *Appl Sci*. 2020; 10(17):5814.
18. Kumar N, Koli DK, Jain V, et al. Stress distribution and patient satisfaction in flexible and cast metal removable partial dentures: finite element analysis and randomized pilot study. *Journal of Oral Biology and Craniofacial Research*. 2021; 11(4): 478–485. Doi: 10.1016/j.jobcr.2021.06.004
19. Messias A, Neto MA, Amaro AM, et al. Mechanical evaluation of implant-assisted removable partial dentures in Kennedy class I patients: finite element design considerations. *Appl Sci* 2021; 11(2): 659. DOI: 10.3390/app11020659
20. Todorovi A, Radovi K, Grbovi A, et al. Stress analysis of a unilateral complex partial denture using the finite-element method. *Mater Technol* 2010; 44(1): 41–47
21. Memari Y, Geramy A, Fayaz A, et al. Influence of implant position on stress distribution in implant-assisted distal extension removable partial dentures: A 3D finite element analysis. *J Dent* 2014; 11(5): 523–530
22. Zarrati S, Bahrami M, Heidari F, et al. Three dimensional finite element analysis of distal abutment stresses of removable partial dentures with different retainer designs. *J Dent* 2015; 12(6): 389–397
23. Shahmiri R and Das R. Finite element analysis of implant-assisted removable partial dentures: framework design considerations. *J Prosthet Dent* 2017; 118(2): 177–186.
24. Eom J-W, Lim Y-J, Kim M-J, et al. Three-dimensional finite element analysis of implant-assisted removable partial dentures. *J Prosthet Dent* 2017; 117(6): 735–742.
25. Tereza Rodrigues M, Harshitha Gowda BH and Alva B. Stress distribution in tooth supported removable partial denture fabricated using two different materials: A 3-dimensional finite element analysis. *Mater Today Proc* 2021; 46: 7643–7650. Elsevier. DOI: 10.1016/J.MATPR.2021.01.943.
26. Shahmiri R and Das R. Finite element Analysis of implant-Assisted removable partial denture Attachment with different matrix designs during bilateral loading. *Int J Oral Maxillofac Implants* 2016; 31: e116–e127.
27. Ibrahim RO, AL-Zahawi AR and Sabri LA. Mechanical and thermal stress evaluation of PEEK prefabricated post with different head design in endodontically treated tooth: 3D-finite element analysis. *Dent Mater J* 2021; 40(2): 508–518.
28. Mohammed JA, Zainab H and Al-Ghurabi. "Radiological assessment of mandibular retromolar canal (MRMC) using CBCT-radiographs in a sample of Iraqi patients." *Journal of Baghdad College of Dentistry* 2016; 28(3): 99–103.
29. Greig V Craig's restorative dental materials, 13th edition. *Br Dent J* 2012; 213: 90. DOI: 10.1038/sj.bdj.2012.659.
30. Park HR, Kim SK, Koak JY, et al. Stress analysis on the different clasps of the removable partial denture by three-dimensional finite element method. *J Korean Acad Prosthodont* 2005; 43: 218–231.
31. Kim D, Park C, Yi Y, et al. Comparison of cast Ti-Ni alloy clasp retention with conventional removable partial denture clasps .*J Prosthet Dent* 2004;91: 374–382.
32. Gharechahi J, Sharifi E, Nosohian S, et al. Finite element method analysis of the stress distribution to supporting tissues in a class IV Aramany removable partial denture (Part I: the

Teeth and Periodontal Ligament). *J Contemp Dent Pract* 2008; 9: 65–72.

33. Gharechahi J, Sharifi E, Nosohian S, et al. Finite element method analysis of stress distribution to supporting tissues in a class IV Aramany removable partial denture (Part II: bone and Mucosal Membrane). *J Contemp Dent Pract* 2008; 9: 49–56.
34. Phoenix RD, Cagna DR and DeFreest CF. *Stewart's clinical removable partial prosthodontics*. Chicago: Quintessence; 2003: pp. 47–49.
35. Wang H-y., Zhang Y-m., Yao D, et al. Effects of rigid and nonrigid extracoronal attachments on supporting tissues in extension base partial removable dental prostheses: A nonlinear finite element study. *J Prosthet Dent* 2011; 105: 338–346.