Original Article

Comparative three-dimensional finite element analysis of implant-supported fixed complete arch mandibular prostheses in two materials

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Abstract

Background: The increase of requests for implant-supported prosthesis (ISP) with zirconia as infrastructure has attracted a lot of attention due to its esthetics, biocompatibility, and survival rate similar to metallic infrastructure. The aim of this study was to evaluate the influence of two different framework materials on stress distribution over a bone tissue-simulating material.

Materials and Methods: Two ISP were modeled and divided into two infrastructure materials: titanium (Ti) and zirconia. Then, these bars were attached to a modeled jaw with polyurethane properties to simulate bone tissue. An axial load of 200 N was applied on a standardized area for both systems. Maximum principal stress (MPS) on solids and microstrain (MS) generated through the jaw were analyzed by finite element analysis.

Results: According to MS, both models showed strains on peri-implant region of the penultimate (same side of the load application) and central implants. For MPS, more stress concentration was slightly higher in the left posterior region for Ti's bar. In prosthetic fixation screws, the MPS prevailed strongly in Ti protocol, while for zirconia's bar, the cervical of the penultimate implant was the one that highlighted larger areas of possible damages.

Conclusions: The stress generated in all constituents of the system was not significantly influenced by the framework's material. This allows suggesting that in cases without components, the use of a framework in zirconia has biomechanical behavior similar to that of a Ti bar.

Keywords: Biomechanics, dental implants, finite element analysis

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INTRODUCTION

The rehabilitation of edentulous jaws with a protocol prosthesis allowed extensive rehabilitations with implants and minimal surgical intervention.[1] However, biomechanical complications may impair the performance of osseointegrated dental implants due to the overload

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capable to induce bone remodeling,[2-4] since human bone tissue is capable to adapt to the amount of load received and to modify itself by remodeling.[5]

For the prosthetic framework, the increase of undesired stress occurs in the supporting tissues due to the fact that the lever arm is larger.[6] To reestablish chewing capacity in the posterior region, masticatory force may need to exist beyond the last implant.[7] Different materials strength used in frameworks is another possible factor to influence directly the success of implant rehabilitation through the dissipation of chewing load.[8,9]

A large number of materials are available to produce a prosthesis infrastructure. It is recommended that metallic alloys exhibit high tensile strength (>300 MPa) and elastic modulus (>80,000 MPa) sufficient to prevent deformations and the cantilevers fractures.[10] The titanium alloy (Ti) has corrosion resistance, biocompatibility, low cost, and mechanical properties similar to auric alloy (good mechanical properties, but high cost) that makes Ti a viable material for the fabrication of prosthesis infrastructure on implants.[11,12]

The increase of requests for metal-free prostheses led to the development of ceramics with esthetics and biocompatibility.[13] The use of implant-supported prosthesis (ISP) with zirconia infrastructure has attracted a lot of attention. As well as esthetics, it presents survival rate similar to metallic infrastructure.[14-16]

Using finite element analysis (FEA) method, it is possible to study the stress generated in periimplant bone tissue on a preventive way.[17,18] FEA consists of a promising noninvasive methodology that provides consistent results through measurement of stress, compression, and displacement in implants and structures involved in rehabilitation.[19] This technique is considered complex due to the involvement of biomaterials properties and microstructural details.[11,13] However, it is widely used in dental implant analyzes.[9,11,13,17,18,20-24]

Several studies that evaluate the biomechanical behavior of ISP's search to simulate a clinical situation and end up also studying the bone adaptive property.[20,21,25-29] However, the cortical bone properties may vary in cadavers[22] because this tissue has anisotropic behavior making its elastic property vary according to the orientation of the cells and fibers present.[28] Thus, to standardize *in vitro* studies and isolate biological variables, resinous materials whose elastic modulus approaches the bone tissue are used,[29] such as, polyurethane.[30]

Assuming that biomechanical behavior of different materials used in the framework of Branemark implant protocol was the goal for several recent researches[20,21,25-27] and due to no study (within the authors' knowledge) used a validated elastic modulus for laboratory studies, the aim of this study was to evaluate the influence of different framework materials (Ti or zirconia) on stress distribution over a bone tissue-simulating material (polyurethane). The purpose of this study was to use computer simulations to examine clinical situations with IPS in edentulous mandibles and identify the biomechanical behavior of two different materials.

MATERIALS AND METHODS

Using computer-aided design Rhinoceros software (Version 5.0 SR8, McNeel North America, Seattle, WA, USA), a model of an edentulous jaw was made following the main anatomical characteristics: size, shape, and absence of pathology. Initially, anatomical lines were constructed so that each face of the outer surface could be obtained by the union of three or four lines. After surfaces creation, they were fixed forming a volumetric solid body of a hemi-jaw. For complete construction of the virtual jaw's model, the bone structure was mirrored from the midline, allowing symmetry between the antimere sides. Then, a Boolean union ensured that a solid arcade was created. Then, external hexagon implants (10 mm × 4.1 mm) were modeled. The external threads diameter was established according to the dimensions provided by the manufacturer (as technology Titanium Fix – São José dos Campos, Brazil), and the platform showed 4.1 mm in diameter such as a conventional regular implant. The external hexagon was extruded 0.7 mm high and attached to the previously created cylindrical body.

The first implant was centrally attached to the mental foramen so that the other four implants could be positioned equidistant from the center [Figure 1]. After modeling all implants in their ideal positions, Universal Castable Long Abutment (UCLA) components were created according to the individual height of each implant and attached to a standard framework model. The retaining screw was also shaped and allocated in its ideal position.

The bar presented a height of 6 mm from the bone surface and a 10 mm lever arm on each side. The orifices of all screws were created to simulate a clinical situation of structural strength of this material. Finally, at the end of the bar, two circles with 2 mm diameter were created on the upper outer surface to standardize the load application.

This study had the characteristic to not allowing results in the mandibular branches. Thus, they were removed from the model to avoid spent elements while exporting idle geometries.

Finite element analysis preprocessing

The Young's modulus and Poisson's ratio of the materials [Table 1] were assigned to each solid component with isotropic, homogeneous, and linearly elastic behavior. All contacts were considered bonded since a torque failure is not the purpose of the study. The same three-dimensional model was used to receive materials properties and generate different results.

Mesh generation

The solid geometries were exported to ANSYS software (ANSYS 16.0, ANSYS Inc., Houston, TX, USA) in STEP format. Then, tetrahedral elements formed the mesh. A convergence test of 10% determined the total number of control elements of the mesh for 370.345 [Figure 2].

Loadings and fixations

The application of an axial load (200 N) followed the delimited area in CAD: unilateral posterior superior region (left side) in the direction of bone. For the fixation condition of the system, the jaw base was selected, ensuring only movement restriction on the Z axis. In this way, the deformation generated in all directions inside the mandible could be computed.

Table 1: Properties of the materials used in finite element analysis methodology

	Young's modulus (GPa)	Poisson's ratio	References
Titanium	110	0.33	[23]
Zirconia	200	0.31	[24]
Polyurethane	3.6 GPa	0.3	[31]

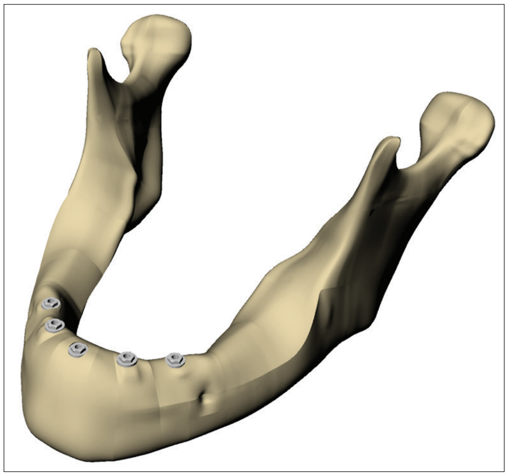

Figure 1: Three-dimensional model of a jaw made in computer-aided design with fixation of the five implants equidistant positioned

RESULTS

The generated results show the maximum principal stress (MPS) in the ductile solids and in the simulator model of the human bone tissue, the microstrains (MSs) generated were evaluated. In both models, a greater tendency of total bone displacement occurred in the marginal area to the last implant (same side of the vertical load application). The energy concentration was slightly higher in the left posterior region for Ti's bar compared to zirconia's bar [Figure 3].

Initially, the MS was presented based on the theory of bone remodeling as a function of the load. According to the images of Figure 4, the regions with masticatory overload may initiate an unwanted bone remodeling. In the generated results, the regions of concentration of strains are both very similar, in which it is not possible to evidence significant difference in the colorimetric graph between both jaw models. The last two implants on the load side received most of the masticatory forces, which shows the consistency of the system. The proximal regions of the periimplant tissue of these two implants were more affected, which suggests the initiation of any bone alteration in this region during this loading.

The MPS showed areas of tensile, which can be understood as areas of possible failure of the structure in the function.

In ductile components of the system, the MPS was also displayed in color scales. For prosthetic fixation screws, the stress prevailed strongly in Ti protocol [Figure 5]. While for zirconia's bar, the platform of the penultimate implant was the one that highlighted larger areas of possible damages [Figure 6].

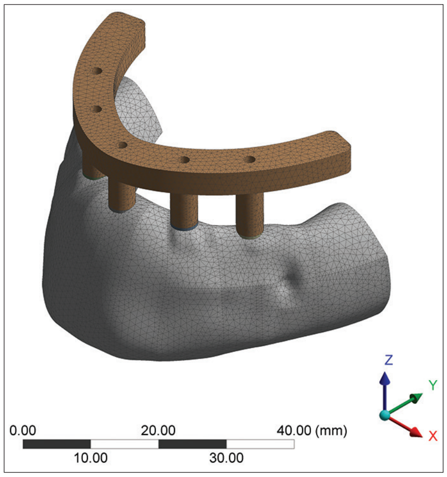

Figure 2: Mesh formed by tetrahedral elements

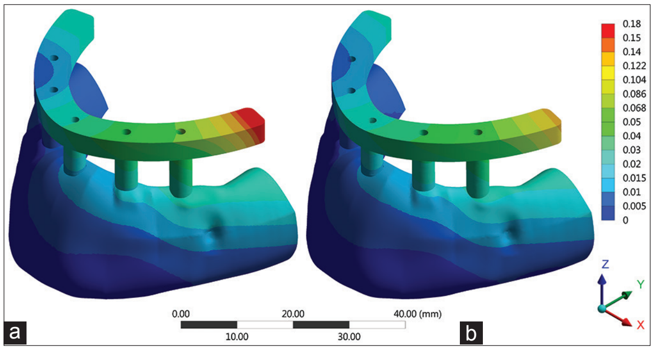

Figure 3: Displacement pattern in the models with energy concentration in the marginal area at the last implant for the bar in (a) titanium (presenting greater tension represented by the red color) and (b) zirconia

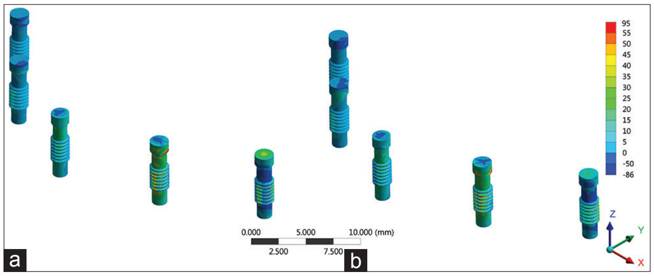

Figure 5: Maximum principal stress in prosthetic fastening screws. (a) The situation with titanium bar. (b) Situation with bar in zirconia

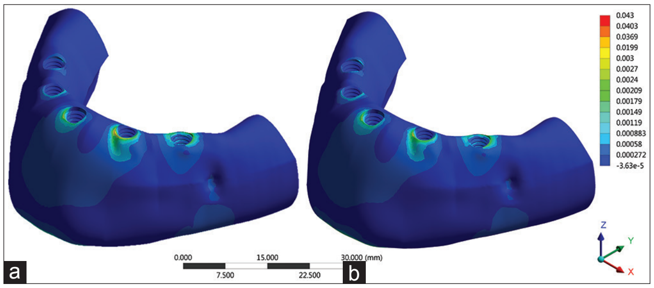

Figure 4: Microstrain distribution pattern in jaw's models under bar in (a) titanium and (b) zirconia

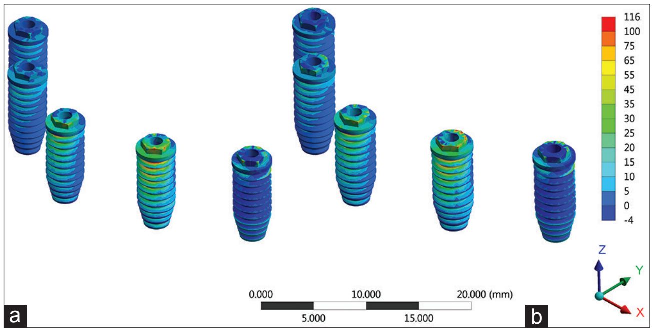

Figure 6: Maximum principal stress on implants. (a) Situation with titanium bar. (b) Situation with zirconia bar

DISCUSSION

In this study, FEA was used to investigate the influence of the two prosthodontic frameworks submitted to an axial load on the biomechanical behavior of isotropic jaws. The analysis of total displacement, consistency, and connectivity of the mesh [Figures 2 and 3], MPS and MS demonstrated that this is a viable model for the analysis using the FEA method. To ensure that the quality of the results would not be compromised due to the complexity of the model's geometry, it was necessary to divide the structure into a finite number of elements with 10% convergence.

The results show not only the stress distribution on the surface of the bone crest but also, the biomechanical behavior of different constituents of this type of rehabilitation treatment with implants. This demonstrated that the framework material minimally influences the distribution of stress in the simulated jaw and implants.

In vivo studies revealed the values of occlusal masticatory force around 220 N in the posterior region.[1,21,32] Thus, a load of 200 N was used in an attempt to simulate a result closer to that observed *in vivo*.

Rubo and Souza (2008)[9] affirmed that the lower elastic modulus, the greater exerted force on the abutments closest to the load. Therefore, if a rubber structure was used, the entire load would be concentrated in the implant closest to the point of load application. The authors concluded that the more rigid structure the more uniform stress dissipation and the less damage caused to the fastening screws due to the bending of the reduced metal structure.

In the present study, two rigid structures were used (Ti and zirconia) with different elastic modulus. The results obtained are consistent since the stress dissipation did not concentrate at specific points as would occur if a flexible structure were used.[9] It is recommended that if a metallic alloy is going to be used, it must have high strength (>300 MPa) and high elastic modulus (>80 GPa) to prevent deformation and structures failure.[33] These are characteristics of less rigid materials than those used in this study.

For both jaw protocol models, the stress fields showed no significant discrepancies. However, a trend of displacement in a wider area of the Ti bar was observed in the region of the lever arm [Figure 3]. The presence of a lever arm has a remarkable effect on stress concentration,[5] and increases of 5 mm elevate the maximum von Mises stress by around 30% to 37% around the implants.[9] According to Glantz,[34] the amount of strain of the lever arm is directly proportional to the length and inversely proportional to the width and height of it. In addition, there is a direct relationship between the amount of strain and the applied load and elastic modulus of the used material. Since zirconia's elastic modulus is 55% larger than Ti modulus, it seems that the influence of the bar's geometry (similar for both models) is much more influential in the results since they were within 10% of convergence [Figure 4]. The results corroborate with the findings of Bankoglu and Yilmaz,[13] where the authors observed that in a fixed partial anterior prosthesis with horizontal load, the maximum stress was similar in the models with zirconia and Ti infrastructure.

Although minute results and similar behavior for the bars, inferences can be made: in the simulated jaw, the generated strains were slightly higher with zirconia bar because stress areas were observed in the penultimate and central implants while compression areas encircled the last implant characterizing it as a fulcrum in a distal rotation tendency of the system [Figure 5]. This tendency of rotation was reflected on the fixation on an inverse way for the two materials. While Ti with similar elastic modulus of the screw allowed stresses passage between them as a single body with less damage to the implant, the zirconia with all the rigidity characteristic of its crystalline structure tended to further damage the prosthetic connection and less the screw [Figure 6].

Currently, zirconium oxide is increasingly used as an infrastructural material for fixed partial implant-supported prostheses[10] since zirconia has high flexural strength (900–1200 MPa) and hardness (1200 Hv), as well as chemical properties such as low corrosion potential and low thermal conductivity.[35,36] A selection factor for the use of zirconia as an infrastructure material is optimized esthetics due to the natural shadow of the substrate, eliminating the grayish effect in the cervical areas of prostheses with metallic alloy infrastructures.[37] As for longevity, several studies have shown that zirconia is not significantly affected by the aging test suggesting a long lifetime.[38]

In the case of the dissipation of masticatory force, other studies obtained high-stress levels located under the applied load, that is, in the working side implants.[20,39] The results obtained in this work suggest that the prosthesis does not transmit the load identically through all implants, but these differences were not significant.

CONCLUSIONS

Within the limitations of this study, it is possible to conclude that the stress generated in all constituents of the system was not significantly influenced by the bar's material. This allows suggesting that in cases without abutments, the use of a framework in zirconia has biomechanical behavior similar to that of a Ti bar.

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Conflicts of interest

There are no conflicts of interest.

REFERENCES

1. Maló P, Rangert B, Nobre M. "All-on-Four" immediate-function concept with Brånemark System implants for completely edentulous mandibles: A retrospective clinical study. Clin Implant Dent Relat Res 2003;5 Suppl 1:2-9.
2. Jemt T, Carlsson L, Boss A, Jörneús L. *In vivo* load measurements on osseointegrated implants supporting fixed or removable prostheses: A comparative pilot study. Int J Oral Maxillofac Implants 1991;6:413-7.
3. Smedberg JI, Nilner K, Rangert B, Svensson SA, Glantz SA. On the influence of superstructure connection on implant preload: A methodological and clinical study. Clin Oral Implants Res 1996;7:55-63.
4. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: Clinical guidelines with biomechanical rationale. Clin Oral Implants Res 2005;16:26-35.
5. Lundgren D, Falk H, Laurell L. Influence of number and distribution of occlusal cantilever contacts on closing and chewing forces in dentitions with implant-supported fixed prostheses occluding with complete dentures. Int J Oral Maxillofac Implants 1989;4:277-83.
6. Falk H, Laurell L, Lundgren D. Occlusal interferences and cantilever joint stress in implant-supported prostheses occluding with complete dentures. Int J Oral Maxillofac Implants 1990;5:70-7.
7. Shackleton JL, Carr L, Slabbert JC, Becker PJ. Survival of fixed implant-supported prostheses related to cantilever lengths. J Prosthet Dent 1994;71:23-6.
8. Isidor F. Influence of forces on peri-implant bone. Clin Oral Implants Res 2006;17 Suppl 2:8-18.
9. Rubo JH, Souza EA. Finite element analysis of stress in bone adjacent to dental implants. J Oral Implantol 2008;34:248-55.
10. Gonzalez J. The evolution of dental materials for hybrid prosthesis. Open Dent J 2014;8:85-94.
11. Ferreira MB, Barão VA, Faverani LP, Hipólito AC, Assunção WG. The role of superstructure material on the stress distribution in mandibular full-arch implant-supported fixed dentures. A CT-based 3D-FEA. Mater Sci Eng C Mater Biol Appl 2014;35:92-9.
12. Simamoto Júnior PC, Resende Novais V, Rodrigues Machado A, Soares CJ, Araújo Raposo LH. Effect of joint design and welding type on the flexural strength and weld penetration of Ti-6Al-4V alloy bars. J Prosthet Dent 2015;113:467-74.
13. Bankoglu Güngör M, Yilmaz H. Evaluation of stress distributions occurring on zirconia and titanium implant-supported prostheses: A three-dimensional finite element analysis. J Prosthet Dent 2016;116:346-55.
14. Mendez Caramês JM, Sola Pereira da Mata AD, da Silva Marques DN, de Oliveira Francisco HC. Ceramic-veneered zirconia frameworks in full-arch implant rehabilitations: A 6-month to 5-year retrospective cohort study. Int J Oral Maxillofac Implants 2016;31:1407-14.
15. Sailer I, Gottnerb J, Kanelb S, Hammerle CH. Randomized controlled clinical trial of zirconia-ceramic and metal-ceramic posterior fixed dental prostheses: A 3-year follow-up. Int J Prosthodont 2009;22:553-60.
16. Takaba M, Tanaka S, Ishiura Y, Baba K. Implant-supported fixed dental prostheses with CAD/CAM-fabricated porcelain crown and zirconia-based framework. J Prosthodont 2013;22:402-7.
17. Khurana P, Sharma A, Sodhi KK. Influence of fine threads

and platform-switching on crestal bone stress around implant-a three-dimensional finite element analysis. J Oral Implantol 2013;39:697-703.

18. Carneiro BA, de Brito RB Jr., França FM. Finite element analysis of provisional structures of implant-supported complete prostheses. J Oral Implantol 2014;40:161-8.
19. Greco GD, Jansen WC, Landre Junior J, Seraidarian PI. Biomechanical analysis of the stresses generated by different disocclusion patterns in an implant-supported mandibular complete denture. J Appl Oral Sci 2009;17:515-20.
20. Tabata LF, Rocha EP, Barão VA, Assunção WG. Platform switching: Biomechanical evaluation using three-dimensional finite element analysis. Int J Oral Maxillofac Implants 2011;26:482-91.
21. Kao HC, Chung WN, Chen FC, Hsu ML, Chang KD. Finite element analysis of different superstructure materials in a single distal implant restoration. J Dent Sci 2008;3:140-9.
22. Peterson J, Dechow PC. Material properties of the human cranial vault and zygoma. Anat Rec A Discov Mol Cell Evol Biol 2003;274:785-97.
23. Verri FR, Santiago Júnior JF, Almeida DA, Verri AC, Batista VE, Lemos CA, *et al*. Three-dimensional finite element analysis of anterior single implant-supported prostheses with different bone anchorages. ScientificWorldJournal 2015;2015:321528.
24. Çaglar A, Bal BT, Karakoca S, Aydin C, Yilmaz H, Sarisoy S. Three-dimensional finite element analysis of titanium and yttrium-stabilized zirconium dioxide abutments and implants. Int J Oral Maxillofac Implants 2011;26:961-9.
25. Ciftçi Y, Canay S. The effect of veneering materials on stress distribution in implant-supported fixed prosthetic restorations. Int J Oral Maxillofac Implants 2000;15:571-82.
26. Ishigaki S, Nakano T, Yamada S, Nakamura T, Takashima F. Biomechanical stress in bone surrounding an implant under simulated chewing. Clin Oral Implants Res 2003;14:97-102.
27. Minoretti R, Triaca A, Saulacic N. Unconventional implants for distal cantilever fixed full-arch prostheses: A long-term evaluation of four cases. Int J Periodontics Restorative Dent 2012;32:e59-67.
28. Currey JD. Bones: Structures and Mechanics. Princeton, NJ: Princeton University Press; 2002.
29. Watanabe F, Uno I, Hata Y, Neuendorff G, Kirsch A. Analysis of stress distribution in a screw-retained implant prosthesis. Int J Oral Maxillofac Implants 2000;15:209-18.
30. Moretti Neto RT, Hiramatsu DA, Suedam V, Conti PC, Rubo JH. Validation of an experimental polyurethane model for biomechanical studies on implant-supported prosthesis – Compression tests. J Appl Oral Sci 2011;19:47-51.
31. Souza AC, Xavier TA, Platt JA, Borges AL. Effect of base and inlay restorative material on the stress distribution and fracture resistance of weakened premolars. Oper Dent 2015;40:E158-66.
32. Morneburg TR, Pröschel PA. Measurement of masticatory forces and implant loads: A methodologic clinical study. Int J Prosthodont 2002;15:20-7.
33. Cox J, Zarb G. Alternative prosthodontic superstructure designs. Swed Dent J Suppl 1985;28:71-5.
34. Glantz PO. Aspects of prosthodontic design. In: Brlnemark PI, Zarb GA, Albrektsson T, editors. Tissue-Integrated Prostheses: Osseointegration in Clinical Dentistry. Carol Stream, IL: Quintessence Publishing; 1985. p. 329-31.
35. Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. Biomaterials 1999;20:1-25.
36. Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: Basic properties and clinical applications. J Dent 2007;35:819-26.
37. Sailer I, Holderegger C, Jung RE, Suter A, Thiévent B, Pietrobon N, *et al*. Clinical study of the color stability of veneering ceramics for zirconia frameworks. Int J Prosthodont 2007;20:263-9.
38. Stawarczyk B, Frevert K, Ender A, Roos M, Sener B, Wimmer T. Comparison of four monolithic zirconia materials with conventional ones: Contrast ratio, grain size, four-point flexural strength and two-body wear. J Mech Behav Biomed Mater 2016;59:128-38.
39. Barão VA, Delben JA, Lima J, Cabral T, Assunção WG. Comparison of different designs of implant-retained overdentures and fixed full-arch implant-supported prosthesis on stress distribution in edentulous mandible – A computed tomography-based three-dimensional finite element analysis. J Biomech 2013;46:1312-20.