A 3-D Finite Element Analysis of a Single Implant Retained Overdenture Reinforced with Short Versus Long Frameworks

Keywords

Dental Implant
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ABSTRACT

Due to its simplicity and patient satisfaction, an implant-retained overdenture has become the most preferred treatment for edentulous patients. Due to the presence of an attachment system at mandibular anterior region, however, base fracture is the most common complication of overdenture. This study aimed to evaluate the stress distribution and deformation on a symphyseal single implant retained mandibular overdenture using a three-dimensional finite element. Zirconia versus acrylic overdenture was investigated. Acrylic overdentures reinforced with short (over inter-canine distance) or long (extending between first molars) zirconia, cobalt-chromium alloy or polyetherketoneketone framework were also investigated. A load of 100 N was applied to the incisal edge of mandibular central incisors at a 30° angle. Results showed that zirconia overdenture had lower von Mises stress and deformation in its components than acrylic. Reinforcement of an acrylic overdenture with cobalt chromium or zirconia short frameworks reduced von Mises stress and deformation on its components. Reinforcement of an acrylic overdenture with polyetherketoneketone framework did not show any significant reduction in von Mises stress and deformation. Therefore, it can be concluded that using zirconia overdenture or reinforcing an acrylic overdenture with cobalt chromium or zirconia framework could increase the longevity of the prosthesis.

INTRODUCTION

Due to its simplicity and patient satisfaction, an implant-retained overdenture has become the most preferred treatment for edentulous patients.[1-3] Using a single implant to support the overdenture has been proposed as the less invasive and cost effective option.[4,5] It also reduces the strain on surrounding bone; those with dome type magnet or ball attachments have similar biomechanical effects[6,7] and survival rate to two implant-retained overdentures.[3,8,9] One of the common limitations with a mandibular single implant-retained, overdentureis the base fracture. This fracture is common at the anterior region where the thickness of overdenture base is reduced due to the presence of attachment system.[10] More importantly is the stress concentration that commonly occurs at the anterior region.[11,12] Furthermore, increasing the masticatory force generation with implant-retained overdentures also increases the possibility of fracture.[10]

Reinforcing the acrylic (polymethylmethacarylate, PMMA), a commonly used material for overdentures, with cobalt chromium (Co-Cr) framework has been attempted to reduce its fracture.[13-16] The esthetic display of metal, allergy and metallic taste are major issues associated with Co-Cr. Polymers with high fracture resistance eg, polyetherketoneketone (PEKK), have been used as a framework for fixed or removable prostheses,[17,18] post-core system,[19,20] implant for spinal and orthopaedic applications and scaffold for permanent implant fixation.[21] PEKK is a semi-crystalline thermoplastic polymer that can be fabricated using different methods of milling and pressing. Due to its high ketone contents, it can be easily modified to improve its mechanical stability and osseointegration.[22,23]

Due its esthetic and high strength, zirconia (ZrO_2) has been recently used as frameworks for crown and partial fixed prosthesis,[24] implants[25] and removable telescopic dentures.[26] Zirconia maxillary complete denture, incorporating CAD/CAM ceria-stabilized zirconia/alumina nano-composite framework, showed no fracture up to 2 years of follow up with improvement in patient satisfaction.[27] When incorporated into acrylic denture base, it reduces denture fracture and improves flexure and impact strength. It also reduces the undesirable properties eg, solubility and water sorption.[28]

A 3-D finite element analysis (FEA) has been widely used as a valuable tool for evaluation of stress and strain distribution in prosthetic dentistry.[15,29-32] It also predicts the possibility of fracture that could occur in most appliances.[33] This study aimed to investigate the biomechanical behaviour of a: a) Single implant-retained acrylic versus zirconia overdenture. b) Single implant-retained acrylic overdenture reinforced with short frameworks made from Co-Cr, ZrO_2 or PEKK and extending over inter-canine distance. c) Single implant-retained acrylic overdenture reinforced with long frameworks made from Co-Cr, ZrO_2 or PEKK and extending between mandibular first molars. Stress distribution and deformation in various components of the overdenture as well its supporting tissues were analyzed using a 3-D FEA.

Null hypotheses: NH1: no significant difference in biomechanical behavior of a single implant-retained acrylic and zirconia overdenture. NH2: reinforcement of an acrylic overdenture with a short framework, made from Co-Cr, ZrO_2 or PEKK, has no effect on the biomechanical behavior of a single implant-retained overdenture. NH3: reinforcement of an acrylic overdenture with a long framework, made from Co-Cr, ZrO_2 or PEKK, has no effect on biomechanical behavior of a single implant-retained overdenture.

MATERIALS AND METHODS

Three different models of a single implant-retained mandibular overdenture were simulated using a 3-D finite element analysis.[31] The implant was placed at the midline (symphyseal region) and attached to the overdenture by ball and socket attachment. In the first model, an acrylic and zirconia overdenture were compared. In second model, the acrylic overdenture was reinforced by a short framework, made from Co-Cr, ZrO_2 or PEKK and extending over the inter-canine distance, were investigated. The third model was like the second one except a long reinforcement framework, extending between mandibular first molars, was used. A schematic representation of different components of the overdenture is represented in Figure 1. In all cases, an acrylic overdenture was used as a control.

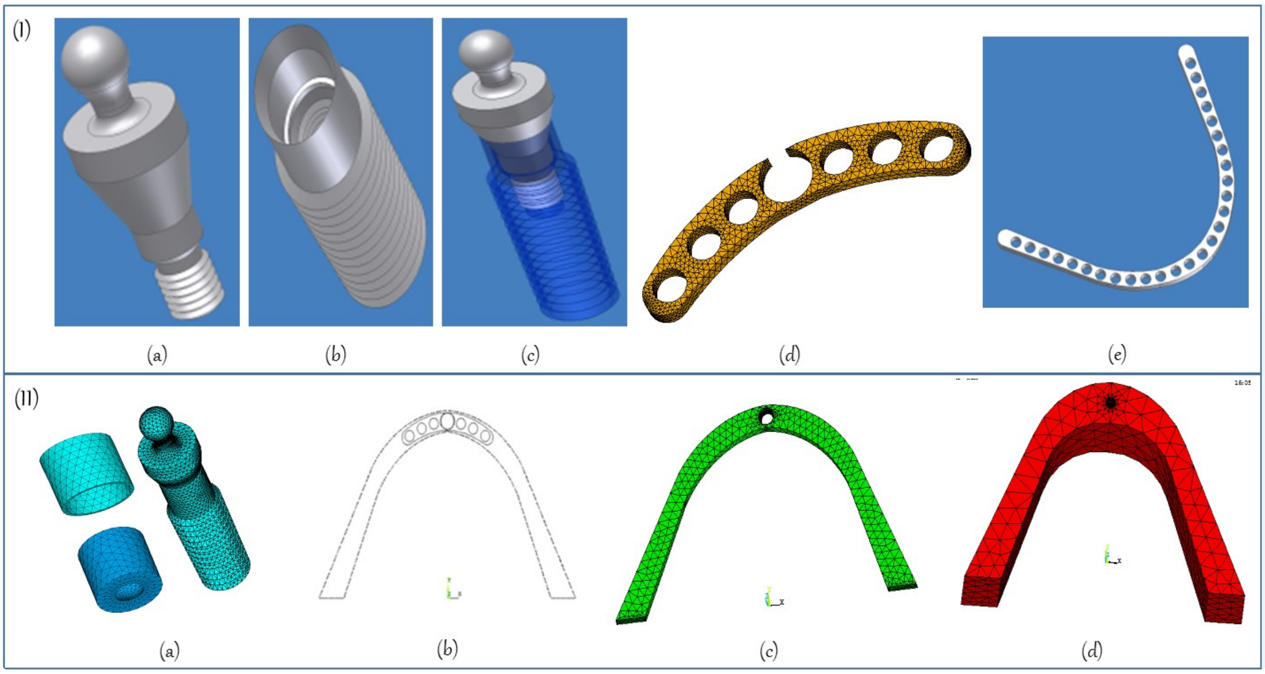

Figure 1: (I) Prosthetic components: low-profile attachment components (a & b), implant (c), short (d) and long (e) framework. (II) Meshed components of the model(s): ball attachment and metal cap (a), short framework (b), long framework (c) and overdenture (d).

Autodesk Inventor" Version 8 was used to create different components of the finite element models. These components include the overdenture, mucosa, caps, implant, frameworks, cortical and cancellous bones. The model was then exported as SAT files. ANSYS environment was used to assemble these components. A root form threaded titanium dental implant with ball and socket attachment and a nominal diameter of 3.75 mm (4.1 mm in platform diameter) and a length of 11 mm was used for the analysis. The following assumptions were considered during the simulation:[32,34] (a) a perfect osseointegration of implant into the surrounding bone surface, (b) the cancellous bone has height of 22mm and width of 14mm, (c) the thickness of cortical bone is 1mm, (d) the thickness of mucosa is 2mm (e) the overdenture has 8mm height and 8.73mm width and (f) all materials used in this study are isotropic, homogenous and linearly elastic. Young's modulus and Poisson's ratio of these materials are given in Table 1.

Table 1. Young's modulus and Poisson ratio of different materials used in the finite element model

Material	Young's modulus [MPa]	Poisson's ratio
Acrylic	8,300	0.28
Cobalt-Chromium (Co-Cr)	218,000	0.33
Polyetherketoneketone (PEKK)	5,100	0.40
Zirconia (ZrO)	268,000	0.30
Mucosa	680	0.45
Nylon Ring (Cap)	350	0.40
Implant	110,000	0.35
Cortical Bone	136,00	0.26
Cancellous Bone	1,360	0.31

Before assembling the complete model(s), a set of Boolean operations between the modelled components was performed using 3D brick solid element "Solid-185" that has 3 degrees of freedom (translations in main axes directions). The resulted numbers of nodes and elements are listed in Table 2. The lowest plane of each model was considered as fixed nodes in the three directions as a boundary condition. For each model, an oblique loading of 100N was applied to the incisal edge of mandibular central incisors at a 30° angle.[6, 29] Linear static analysis was performed on a Workstation HP Z820, using a commercial multipurpose finite element software package (ANSYS version 16.0). The results of these models were verified against similar studies[28,34] and evaluated qualitatively through the stress distribution and quantitatively through von Mises stress (MPa) and deformation (mm) generated in each component of the models.

RESULTS

A summary of von Mises stress (MPa) and deformation (mm) produced within different components of the model, used in this study, is presented in Table 3 and 4.

Regarding the von Mises stress and deformation generated in cortical bone, zirconia overdenture produced the lowest stress and deformation on cortical bone. The acrylic overdenture reinforced with ZrO or Co-Cr short framework produced moderate stresses and deformation on cortical bone. Reinforcement of an acrylic overdenture with a short PEKK framework however produced no significant change in stresses and deformation on cortical bone. Short frameworks produced lower stress and deformation than long frameworks. This difference however is not significant (*Figure 2*).

Regarding the von Mises stress and deformation generated in cancellous bone, the lowest values were recorded with zirconia overdenture. Reinforcement of acrylic overdenture with short or long framework produced no significant change in stress and deformation. Regarding the von Mises stress and deformation generated in mucosa, they were reduced by ~60 and 42% with zirconia overdenture when compared with acrylic. Reinforcement of acrylic overdenture with short Co-Cr or zirconia framework produced a significant reduction in von Mises stress. Generally, reinforcement of an acrylic overdenture with PEKK or any long framework produced no significant change in both stress and deformation.

Regarding the von Mises stress and deformation generated in an overdenture, with all models, the maximum deformations and stresses was observed at the incisor area. Zirconia overdenture received significantly higher von Mises stress but lower deformation than acrylic. Reinforcement of acrylic overdenture with short zirconia or Co-Cr or long PEEK framework produced a non-significant reduction in stress and deformation. Using long zirconia framework produced the highest von Mises stress and deformation (*Figure 3*).

Regarding the von Mises stress and deformation generated in an implant, in all cases, the highest deformations and stresses appeared at its neck towards the applied load. With zirconia overdenture, the lowest von Mises stress and deformation was observed on the implant. A significant reduction in von Mises stress and deformation was only observed when the acrylic overdenture was reinforced with short or long Co-Cr framework (*Figure 4*). Regarding the von Mises stress and deformation in nylon and metal cap, only zirconia overdenture showed a significant reduction in both von Mises stress and deformation when compared with acrylic overdenture.

DISCUSSION

It has been proven that a single implant-retained overdenture does not cause any damaging strain on peri-implant tissues. Therefore, it was considered as a successful treatment option for compromised completely edentulous patients.[6,35,36]

Table 2. Number of nodes and elements in all meshed components.

Model Component	Overdenture		Short Frame		Long Frame	
	Elements	Nodes	Elements	Nodes	Elements	Nodes
Overdenture	15,624	1,563	45,708	5,469	32,624	4,851
Framework	----	----	12,153	1,040	14,363	1,517
Mucosa	4,747	227	4,747	227	4,747	227
Metal Cap	1,352	365	1,534	512	1,534	512
Nylon Ring (Cap)	5,061	545	5,061	545	5,061	545
Implant	120,214	17,690	120,214	17,690	120,214	17,690
Cortical Bone	105,925	3,275	105,925	3,275	105,925	3,275
Cancellous Bone	14,310	1,026	14,310	1,026	14,310	1,026

Table 3. von Mises stress, in different components of overdenture and its supporting tissues due to application of an oblique load of 100N at the incisal edge of mandibular central incisors at 30°. * shows significant difference from acrylic overdenture.

Model Component	Types of overdenture		Types of short framework used for reinforcement of acrylic overdenture			Types of long framework used for reinforcement of acrylic overdenture		
	Acrylic	ZrO_2	ZrO_2	Co-Cr	PEKK	ZrO_2	Co-Cr	PEKK
Cortical Bone	7.32	3.91*	6.45*	6.54*	7.42	7.20	6.51	7.67
Cancellous Bone	0.82	0.53*	0.81	0.80	0.82	0.81	0.80	0.83
Mucosa	14.16	5.53*	12.12*	12.32*	14.34	13.99	13.33	14.92
Overdenture	9.37	20.96*	9.27	9.26	9.47	27.83*	8.98	9.30
Implant	40.68	9.80*	39.94	36.40*	41.16	38.91	35.89*	42.53
Nylon Cap	2.59	1.28	2.45	2.46	2.60	2.56	2.49	2.62
Metal Cap	32.28	5.39	35.27	35.22	34.72	25.48	25.39	25.88

Table 4. Deformation (mm), generated in different components of overdenture and its supporting tissues due to application of an oblique load of 100N at the incisal edge of mandibular central incisors at 30°. * shows significant difference from acrylic overdenture.

Model Component	Types of overdenture		Types of short framework used for reinforcement of acrylic overdenture			Types of long framework used for reinforcement of acrylic overdenture		
	Acrylic	ZrO	ZrO	Co-Cr	PEKK	ZrO	Co-Cr	PEKK
Cortical Bone	0.0025	0.0015*	0.0024	0.0024	0.0025	0.0025	0.0024	0.0026
Cancellous Bone	0.0024	0.0015*	0.0023	0.0023	0.0024	0.0027	0.0022	0.0024
Mucosa	0.0072	0.0042*	0.0069	0.0070	0.0073	0.0123	0.0069	0.0074
Overdenture	0.0098	0.0042*	0.0094	0.0094	0.0099	0.0163*	0.0093	0.0098
Implant	0.0050	0.0021*	0.0045	0.0045*	0.0050	0.0049	0.0044*	0.0052
Nylon Cap	0.0080	0.0040	0.0076	0.0077	0.0082	0.0080	0.0077	0.0083
Metal Cap	0.0081	0.0041	0.0077	0.0077	0.0082	0.0080	0.0077	0.0083

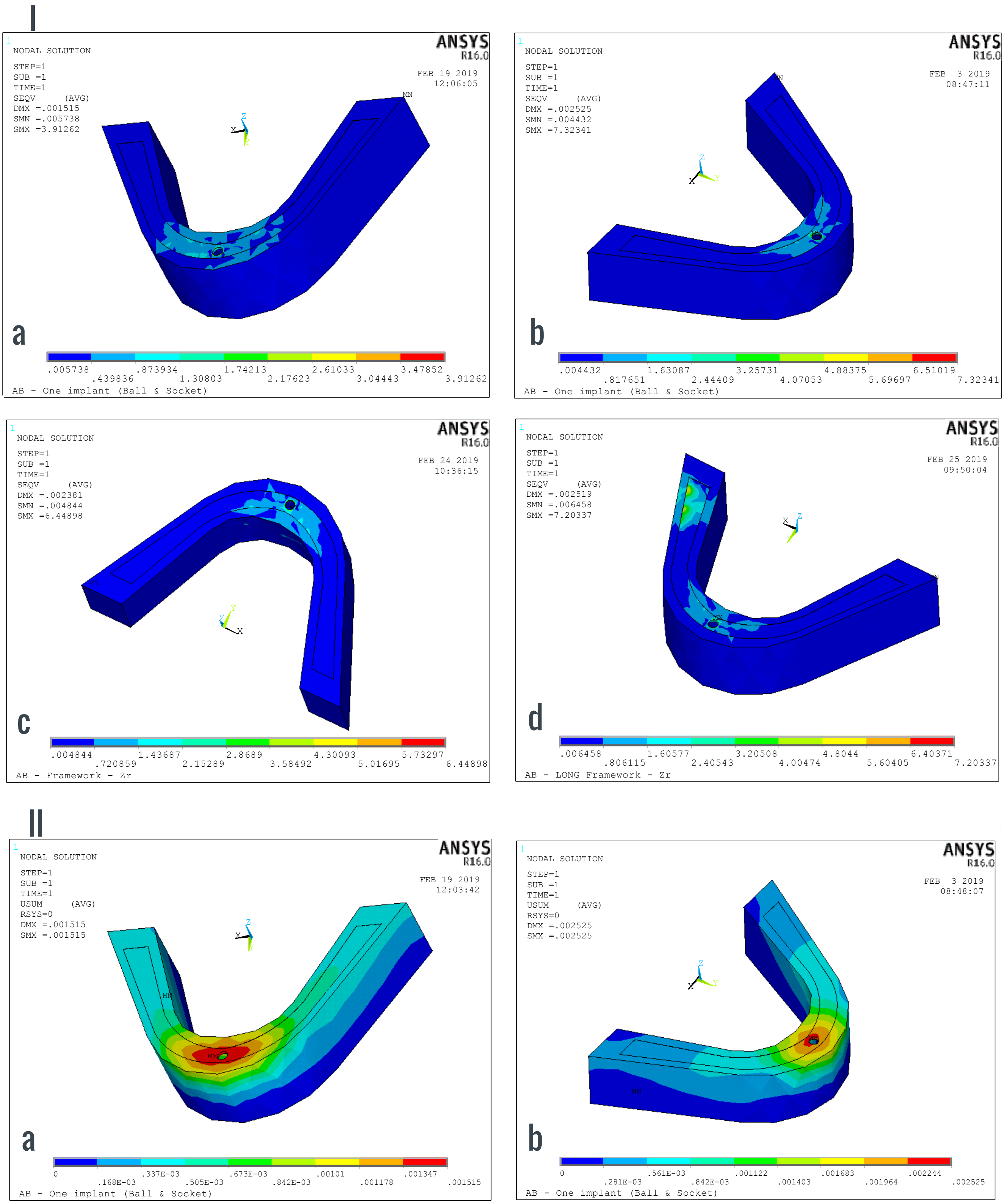

Figure 2: (I) von Mises stress in cortical bone under: (a) zirconia, (b) acrylic overdenture, acrylic overdenture reinforced with short (c) and long (d) zirconia framework. (II) Total deformation of cortical bone under: (a) zirconia and (b) acrylic overdenture.

The coping imbedded inside the denture base however reduced the thickness of acrylic resin in its area. Denture fracture and reduced longevity of the prosthesis will subsequently occur.[15,37] Several methods, used to improve the fracture strength of a single implant-retained overdenture, have been poorly investigated. Throughout this study, zirconia was used as alternative to acrylic as overdenture base. Short or long framework, made from Co-Cr or ZrO_2 or PEKK, was also used to

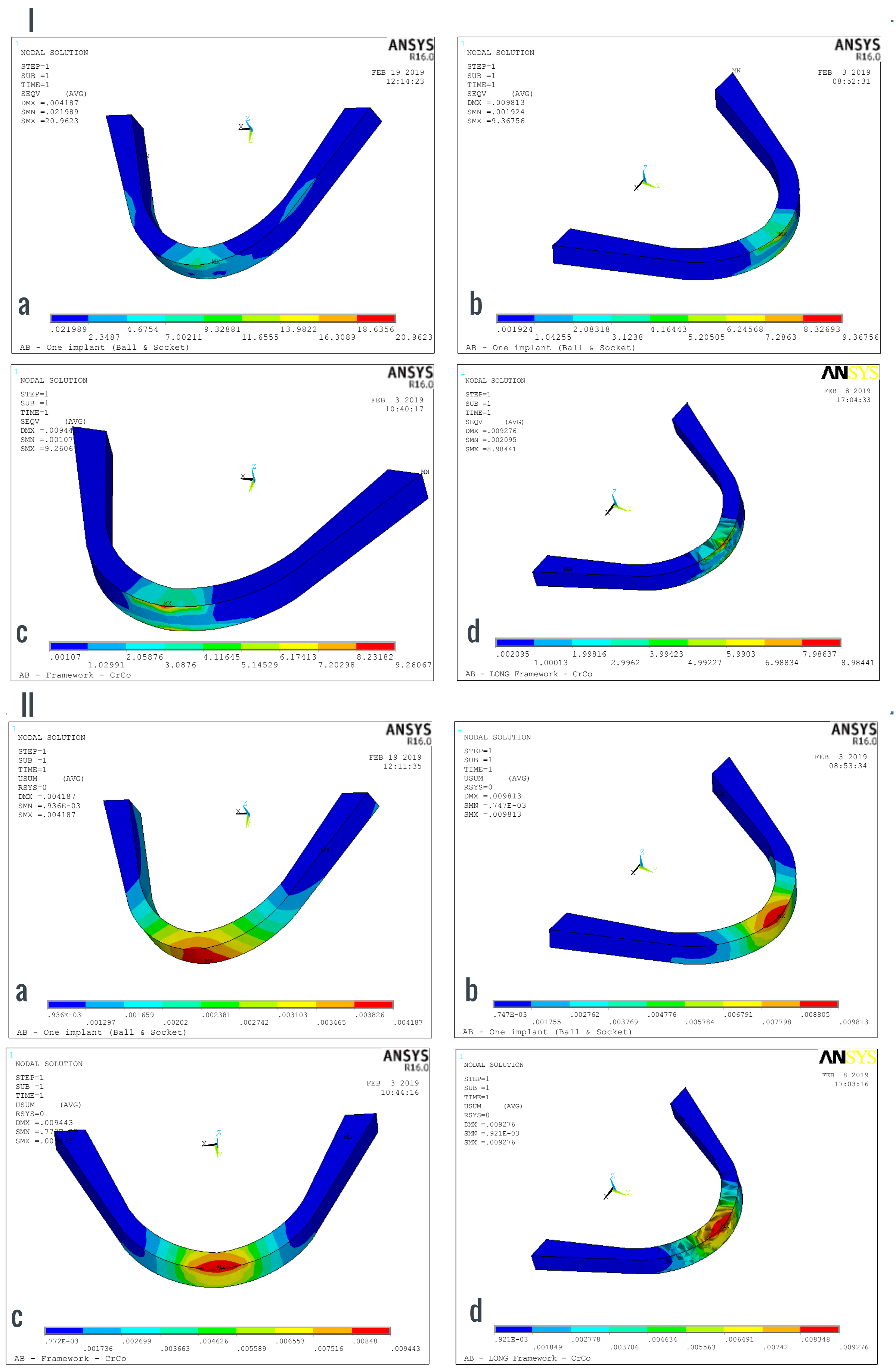

Figure 3: (I) von Mises stress in: (a) zirconia, (b) acrylic overdenture, acrylic overdenture with short (c) and long (d) zirconia framework. (II) Total deformation of: (a) zirconia, (b) acrylic overdenture, overdenture with short (c) and long (d) Co-Cr framework.

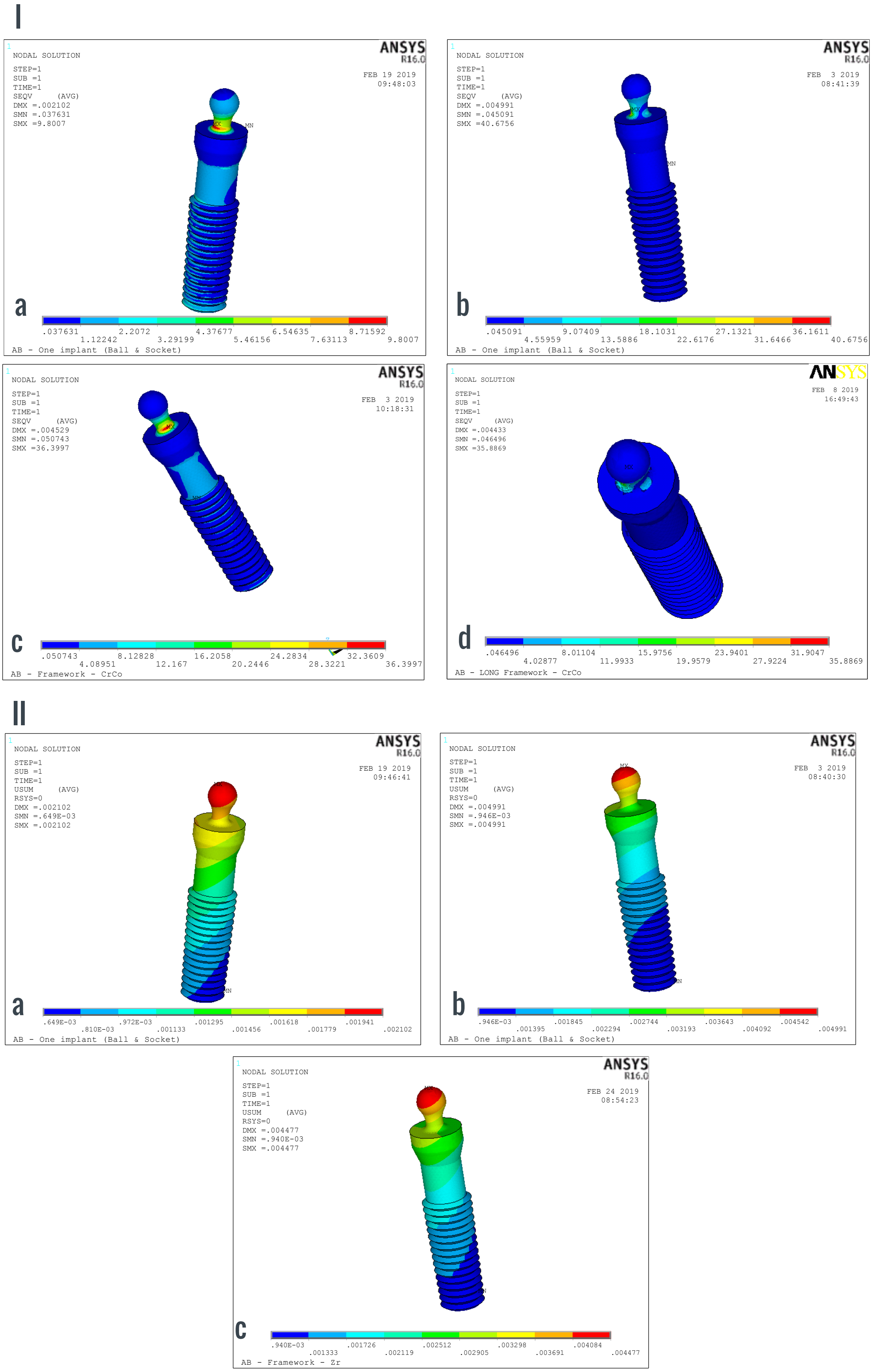

Figure 4: (I) von Mises stress in implant under: (a) zirconia, (b) acrylic overdenture, overdenture with short (c) and long (d) Co-Cr framework. (II) Total deformation of implant under: (a) zirconia, (b) acrylic overdenture and (c) overdenture with short zirconia framework.

transfer the applied load away from the incisor area of acrylic overdenture, the most common site of fracture. Normally, most of the applied loads are received by the implant. Using framework, particularly long, would be expected to transfer minor load to the rear part of the mandible. The effect of such modifications on the biomechanical behaviour of overdenture and its surrounding tissues was the main aim of this study. An oblique force applied at 30° on incisal edge of mandibular central incisors has been employed to resemble the eating movement of a patient wearing a single implant-retained overdenture.

Dental structures are non-homogenous, viscoelastic, and anisotropic. FEA cannot therefore fully represent the complexity of these biological tissues, and the calculated values for stresses and deformation are relative rather than absolute. Furthermore, the interaction that occur in reality between the implant and surrounding tissues could be simulated by FEA provided that detailed information about different materials properties, bone geometry, implant length and diameter as well as the nature of bone-implant interface are known.[30] Regardless of these limitations, FEA is one of the most preferred tools for studying stresses in dental tissues.[38]

Using zirconia instead of acrylic overdenture significantly reduced von Mises stress and deformation on different components (bone, mucosa, implant, nylon mesh and metal cap) but not on the overdenture base itself. Regardless of this high stress on zirconia overdenture, the resultant deformation was lower than that recorded with acrylic and this could be attributed to the high rigidity of zirconia. Accordingly, zirconia overdenture would have longer lifetime than acrylic. Therefore, there is no reason to accept the null hypothesis (NH1).

Reinforcing the acrylic overdentures with short or long framework from Co-Cr or ZrO_2 reduces the von Mises stress and total deformation in overdenture base particularly around the implant; this could be attributed to high rigidity of zirconia and Co-Cr (ie, they withstand most of these stresses and do not transfer them to adjacent tissues). This reduction in stress and deformation around the implant is an essential requirement for decreasing the possibility of overdenture fracture in anterior area and hence improving its longevity.[4,15] PEKK, however, has the tendency to transfer stresses to the surrounding rigid materials.[39] Reinforcement of overdenture with a short framework from ZrO_2 or Co-Cr alloy produced no changes in stress distribution on cancellous bone, nylon cap or metal cap. This was expected since the majority of these stresses is usually received by the implant due to its close location to the applied loads.[15] The difference between short and long frameworks was negligible.

CONCLUSION

Within the limitations of this study, it can be concluded that the overdenture, implant complex and cortical bone are sensitive to reinforcing the acrylic overdenture with a rigid, short, or long framework. Other structures, however, are insensitive to such change and any variation in results may be disappeared by changing bite locations.

So, based on the findings of this FEA study, the following conclusions might be drawn:

- Zirconia overdenture showed the lowest von Mises stress and deformation in all components of a single implant-retained overdenture. Thus, a rigid overdenture is usually recommended.
- Reinforcing an acrylic overdenture with a zirconia or Co-Cr short framework, extending over inter-canine distance, improves the mechanical behavior of a single implant retained overdenture.
- Short frameworks recorded lower von Mises stress and total deformation than longer ones, indicating longer lifetime for incisor loading.
- PEKK is not the material of a choice for reinforcing an acrylic overdenture.

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MANUFACTURERS' DETAILS

- Autodesk Inventor" Version 8 (Autodesk Inc., San Rafael, CA, USA)
- ANSYS environment (ANSYS Inc., Canonsburg, PA, USA)
- Root form threaded titanium dental implant (Zimmer dental Inc, USA)
- Workstation HP Z820 (Dual Intel Xeon E5-2670 v2 processors, 2.5 GHz, 64.0 GB RAM)

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