A Three-Dimensional Finite Element Analysis for Overdenture Attachments Supported by Teeth and/or Mini Dental Implants

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Abstract

Purpose: The aim of this study was to establish the optimum design and attachment combination to support an overdenture with minimal stress and flexing produced in the alveolar bone surrounding any natural teeth and/or mini dental implants.

Materials and Methods: Twelve models were included in the study: the six main models (A, B, C, D, E, and F) were categorized according to the support designs of the overdenture prosthesis, and each model was further subdivided according to the attachment combinations into model 1: with Dalbo elliptic and/or O-ring attachments only and model 2: with flexible acrylic attachments. Vertical loads (35 N) and 17.5 N lateral loads under static conditions were applied to the models to simulate the occlusal forces following the concept of lingualized occlusion. All conditions were created using a finite element software program. Maximum von Mises stress at the level of the attachments and at the bone support foundation interfaces were compared in all 12 models. The flexing of the mandible and the attachments were also compared qualitatively.

Results: Stress on these models was analyzed after the given loading condition. The results showed that the model with three freestanding mini dental implants and flexible acrylic attachments showed the lowest von Mises stress and flexing, while the models with four freestanding mini dental implants and O-ring attachments showed the highest von Mises stress.

Conclusion: Three freestanding mini dental implants with flexible acrylic attachment systems supporting an overdenture were better choices than four mini dental implants with O-ring attachment systems, which showed the maximum flexing and stress values in this qualitative comparison.

In general, it is important to use any abutment options available in the preparation of removable partial prostheses to achieve favorable support and retention.[1] From a functional perspective and according to generally applicable prosthetic concepts, a triangular and/or quadrangular abutment arrangement in the mandible is considered a favorable method of support.[2] Overdentures supported by natural teeth roots are a frequent treatment modality that also follow these principles.[3] However, individuals with a partially edentulous residual ridge with one or two remaining natural teeth roots on one side require the placement of a strategic implant on the opposite side of the arch to equalize the balance and create suitable support and retention. Further investigation is needed in these cases to select the optimum designs to address this problem.[4]

Patients who are originally adaptive to wearing complete dentures may become maladaptive with time, due to ongoing residual ridge resorption, physiological intraoral changes, and the development of altered muscular patterns. It is, therefore, acknowledged that patients with removable overdentures supported and retained either by tooth roots or implants have more predictable prosthodontic outcomes.[5]

Fortunately, implant-supported overdentures in the mandible have been well documented in clinical investigations and are recommended as standard treatment.[3] Even though the principle of using an implant combined with natural teeth to support a denture bas been disputed, except for removable prostheses, the combined use of residual teeth and strategically placed implants in a favorable arrangement will provide a wide range of new and optimized treatment options, and thus offer an extensive and almost unlimited spectrum of new treatment possibilities.[6] However, these combinations of treatment modalities have not been sufficiently investigated in the literature, and further study is needed to select the optimum treatments.

The purpose of this study, therefore, was to compare the stress and elastic flexing of three attachment systems and four mandibular overdenture designs retained by tooth roots and/or mini dental implants (MDIs) only at attachment and alveolar bone levels. The first null hypothesis was that no difference would be found in stress and flexing values when O-ring and Dalbo Elliptic (Cendres+Métaux SA, Biel, Switzerland), attachments were used to retain the overdenture compared with flexible acrylic attachments. The second null hypothesis was that no difference would be found in stress and flexing values when the overdenture supported by teeth and MDIs was compared with an overdenture supported by an MDI only.

Table 1 Properties of materials included in the 3D FEA

Materials	Elastic modulus (*E*) (*MPa*)	Poisson's ratio (*V*)
Acrylic resin[9]	26.500	0.35
Flexible acrylic attachment[10]	7.500	0.30
Dalbo elliptic attachment and O-ring attachment (plastic rubber)[11]	4	0.37
O-ring frame (stainless steel)[11]	205.000	0.30
Titanium[9]	103.400	0.35
Mucosa[9]	1	0.37
Dentin[12]	18.600	0.31
Periodontal ligaments[12]	2	0.45
Cortical bone[13]	13.700	0.30
Cancellous bone[13]	1.370	0.30

Materials and methods

3D finite element models

This study was performed in three stages: (1) the creation of a solid model of the mandible, MDI, screw, natural teeth as two layers (outer periodontal shell and inner dentin layer), attachments, and complete denture; (2) the creation of a finite element (FE) model; and (3) overlapping and gluing the parts of the models to act as one solid body with different material properties, then analyzing the process of load transfer and stress distribution using the facility available in the ANSYS v.13.0 FE software (Swanson Analysis Systems, Houston, PA).

The most important point on which the finite element analysis (FEA) depends is accurate representation. In this study, the mandibular bone geometry was obtained using a structural light scanner (Infocus, Wuhan, China) with Powerscan v3.0 software (Nissin Ltd. Inc., Tokyo, Japan) by scanning different aspects of the mandible model and then assembling them to obtain a solid body with surface simplifications. The model was exported as a UNIGRAFIX (UG) file format to be imported by UG software (UGS NX 7.0, Siemens PLM Software, Camberley, UK) for editing. The geometry of the mandibular bone was modeled with two volumes, that is, an outer shell with an average thickness of about 2 mm representing the cortical bone layer and an inner volume representing the cancellous bone tissue assumed to be perfectly connected with the cortical layer, with the quality of alveolar bone type D2.[7]

A dental implant, Dalbo Rotex screw (Cendres+Métaux SA), natural teeth, and the geometries of their attachment systems (O-ring, Dalbo elliptic and flexible acrylic attachments) were made with custom-made preprocessing tools using measurements available from the manufacturing companies. These custom-made preprocessing tools were developed as part of a commercial software program UGS NX 7.0, which is able to produce the primary topology of each model through a cubic interpolation algorithm. The dimensions and geometries of natural tooth roots, MDI, and Dalbo Rotex screws are shown in Figures 1 and 2. The length of the bone/implant interface was 10 and 14 mm for the tooth/bone interface. The osseointegration of the MDI was assumed to be 100%, which prevented any sliding and rotational movement of the implant at the bone/implant interface. Attachment dimensions included in the study are summarized as follows: Dalbo elliptic attachments (height 3.1 mm, width 4 mm; CM Swiss Dalbo System, Toronto, ON, Canada), O-ring attachments (height 3.5 mm, width 4 mm; Anthogyr, Sallanches, France), and fabricated flexible acrylic attachments (height 4 mm, width 4 mm; Valplast Flexi-acrylic, GC, Shenzhen, China).

A complete denture was constructed by pouring stone material into the edentulous maxillary and mandibular mold. One layer of base plate wax was adapted over the stone cast. Pilkington-Turner 20-degree plastic denture teeth (Dentsply International Inc., Sichuan, China) were set on a flat plane parallel to the ridge with the central fossa centered over the ridge crest. The denture was fabricated on the stone cast using conventional dental laboratory techniques. Modeling of the complete lower denture was done using a section made in a buccolingual direction at midline, the area of the canine-premolar, premolar-molar, and molar-retromolar pad. A dental Vernier caliper was used for the measurement of the complete lower denture section; the final geometrical shape of the complete denture was generated by custom-made preprocessing tools developed as part of the UGS NX 7.0 software. To evaluate the attachments, bone stress, and flexing of different configurations of attachments and the overdenture support foundations, 12 models were included in this study and analyzed by ANSYS software v.13.0 (Fig 3).

Model generation

Numerical models were generated by means of SOLID187 default element size,[8] a higher order 3D 10-node element with a quadratic displacement behavior. The element was defined as having 10 nodes with 3 degrees of freedom at each node, which are translations in the nodal x, y, and z directions. The elements have four triangular faces (Fig 4).

The material properties applied in this study were specified in terms of Young's modulus and Poisson's ratio for all model components (Table 1). All material properties were assumed to be homogeneous, elastic, isotropic, and linear in behavior.

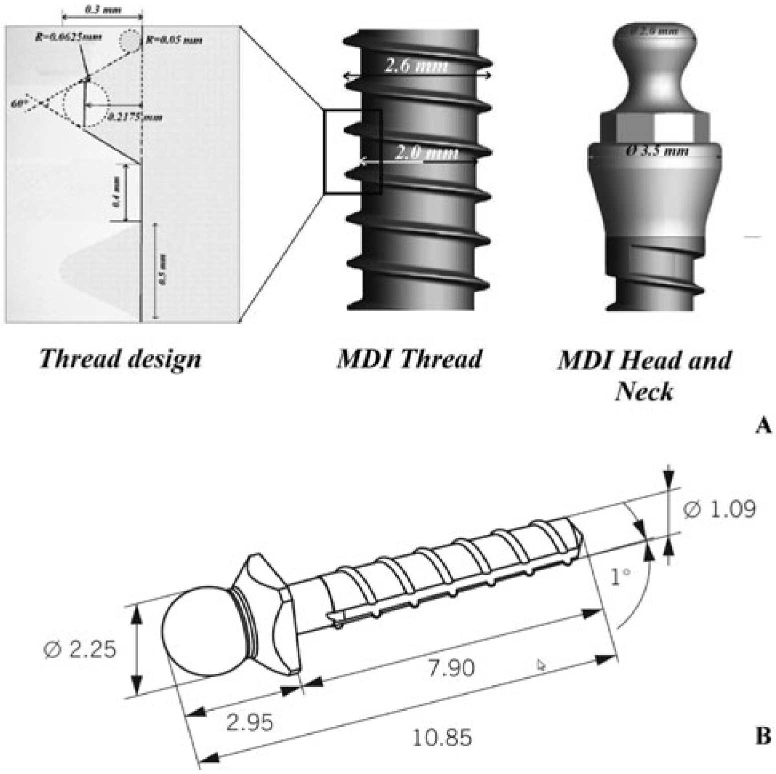


Figure 1 (A) MDI geometries and dimensions. (B) Dalbo Rotex screw geometries and dimensions.

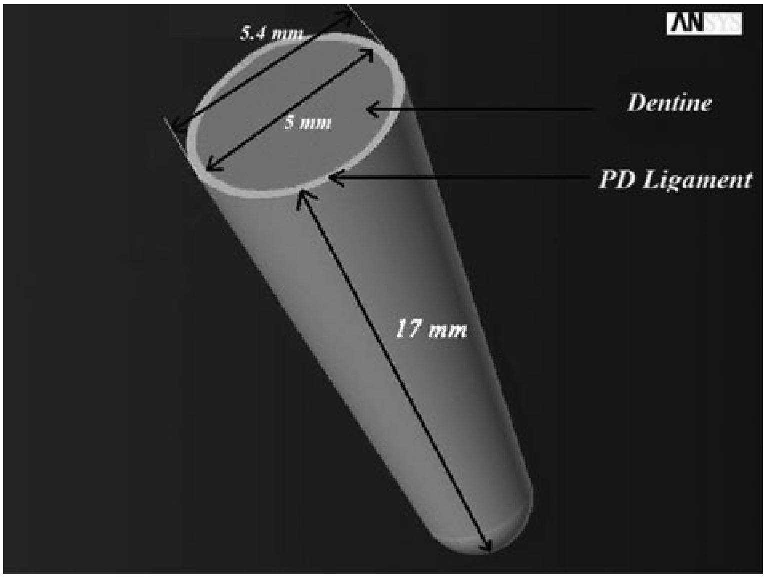


Figure 2 Natural tooth root geometries and dimensions.

Applied boundary conditions

Displacement functions were assumed to be continuous at possible interfaces between different model parts. The properties of the final model were acquired by overlapping and gluing the parts of the model together after generating them (Figs 5A, B). The end section of the bone segment in parallel to the x-y plane was assumed to be fixed so that all nodal displacement was set equal to zero at this section. 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 superio-inferior) to stabilize the model during application of force on the occlusal surface of the denture.

It is important to consider a combination of axial and horizontal load on the assumption that an in vivo load of an overdenture prosthesis occurs in two directions, the horizontal force being approximately 50% of the axial force oriented either in a

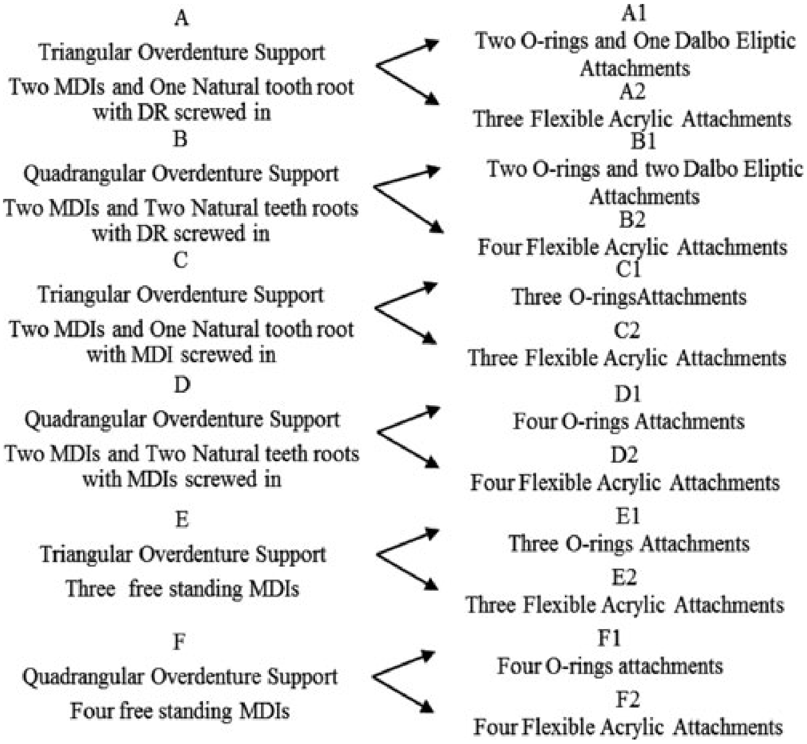


Figure 3 Schematic diagram illustrating the models included in the FEA study.

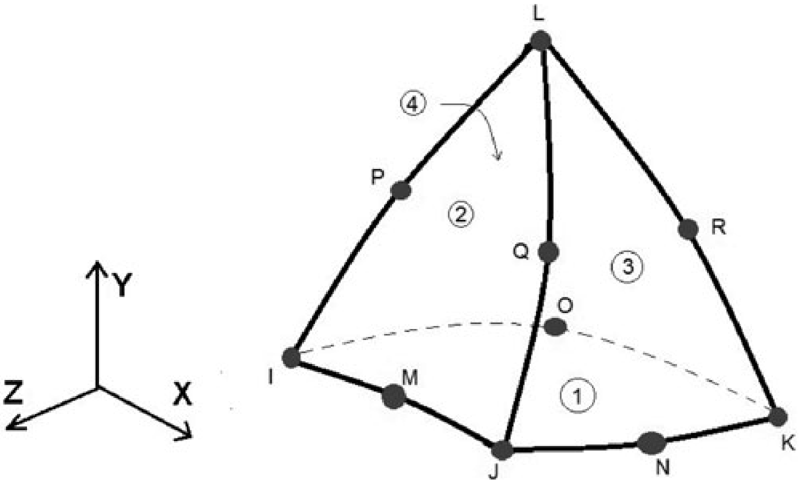


Figure 4 Three-dimensional 10-node elements with a quadratic displacement behavior (SOLID 187 element).

buccolingual or mesiodistal direction.[14] The load applied in this study was 35 N[15] directed axially 0° to the long axis of support at four areas selected with seven nodes included in the –z direction (Fig 6) (5 N on each node), following the concept of lingualized occlusion, [16] while a load of 17.5 N was applied in a horizontal direction parallel to the ±x-axis on the same nodes selected for load applied in the z direction (2.5 N on each node).

Model analyses

The analysis was carried out using ANSYS software v.13.0 and was processed by a personal computer (Founder, Founder Inc, Beijing, China). Stress and flexing on these models were analyzed after the given loading conditions.

Results

The stress analysis executed by ANSYS software v.13.0 provided results that enabled the tracing of the global and detailed graphics of the maximum flexing and von Mises stress fields. Only the von Mises stress (stress equivalent) magnitude values were considered. The effect of all six stress components was summarized with a unique value (x, y, z, xy, zy, zx direction of stress). The maximum von Mises stress values (σ'_{VM}) were noted on the different configurations of attachments and on the

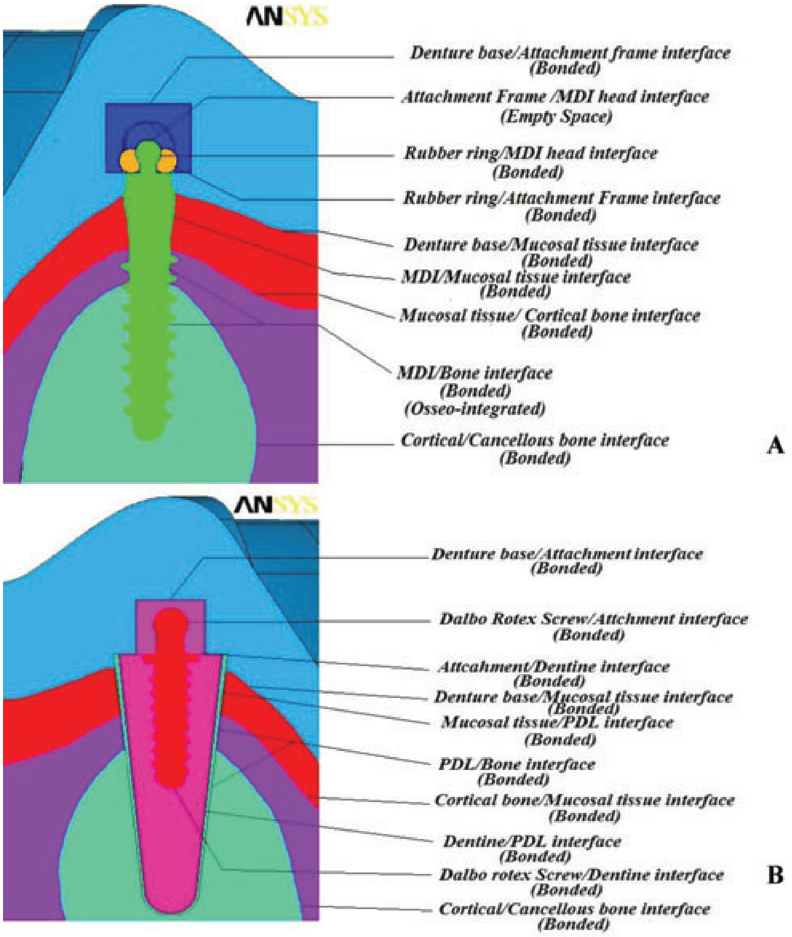


Figure 5 (A) and (B): Contact and interfaces of FE model.

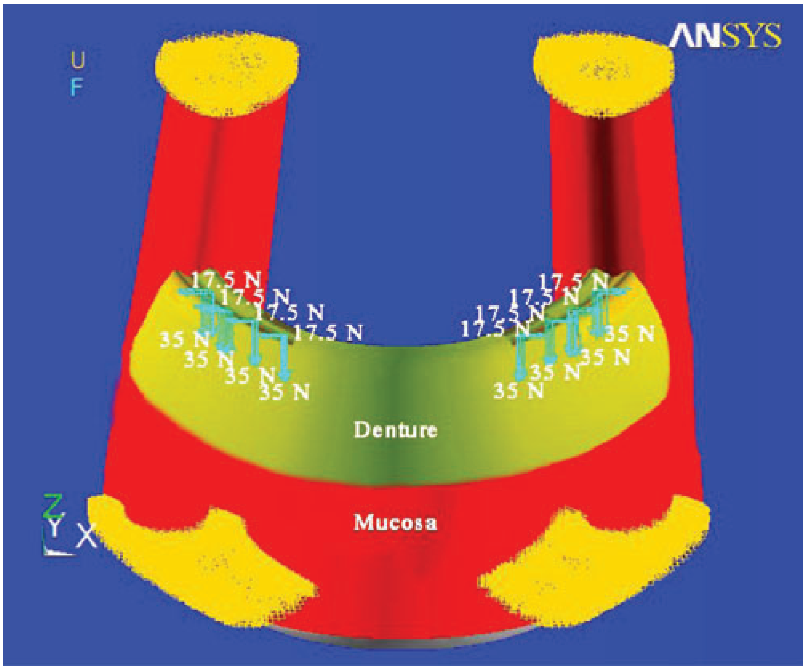


Figure 6 Sites of occlusal loads according to the lingualized occlusal concept.

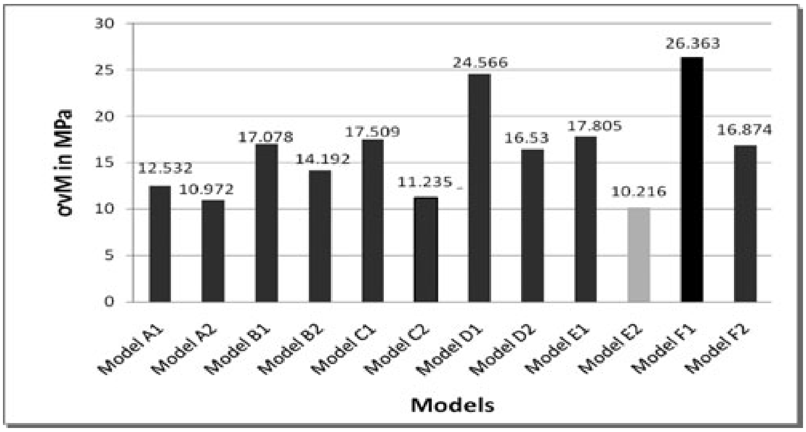


Figure 7 Maximum Von Mises stress (MPa) at attachment level.

interface between the overdenture support and the bone that resulted from combined axial and lateral occlusal loads at sites determined using the lingualized occlusal concept.

Comparing von Mises stress at attachment levels

The stress analysis revealed that σ_{vM}, indicated by a yellow and red colored contour level, occurred at the midline implant attachments for models A1, C1, and E1 while for models A2, C2, and E2 it was located at the side implant attachments and the body of the mandible. Conversely, the σ_{vM} color contour for models B, D, and F showed that maximum stress occurred at the distal implant attachment. When comparing maximum stress at the attachment level, the highest σ_{vM} was observed on model F1 with the lowest on model E2 (26.363 MPa and 10.216 MPa, respectively). Models A2 and C2 showed nearly similar levels of stress to model E2 (10.972 MPa, 11.235 MPa, and 10.216 MPa, respectively). The comparative study of σ_{vM} of models at the level of the attachments is shown in Figures 7–9, and the magnitude of the stress in the models is shown in Table 2.

Comparing Von Mises stress at the bone/overdenture support foundation level

Stress was also evaluated at the interface of the overdenture support foundation and the bone. The comparative evaluation of the σ_{vM} stress field revealed similar results to the stress comparison at the attachment level, in that the maximum stress concentration was noted on model F1, while the lowest was found on model E2. Model D2 showed a nearly similar σ_{vM} to that obtained in model E2 (Table 2).

Comparing maximum flexing at attachment and mandibular bone levels

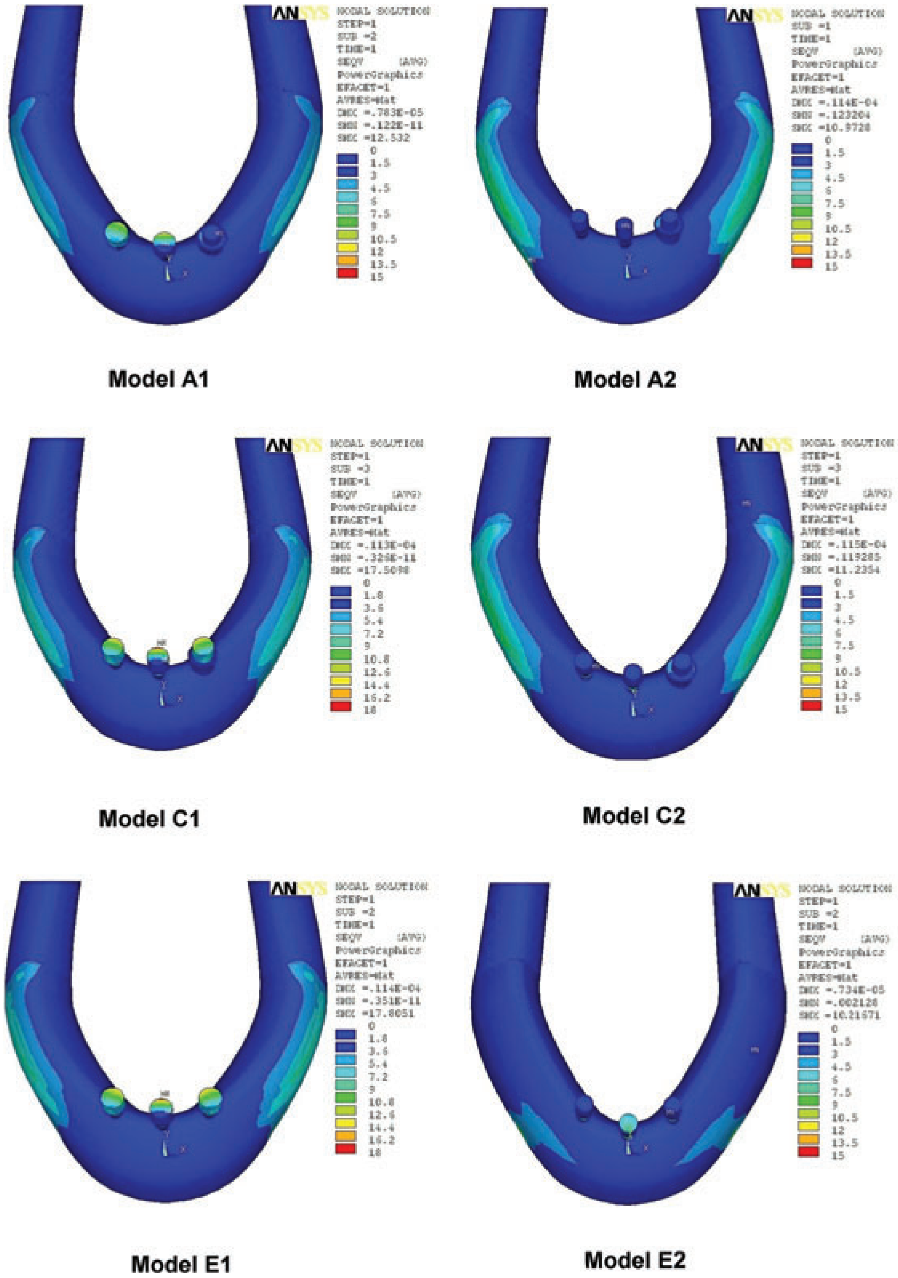
Flexing of the attachment and the mandible, was noted on static loading conditions. The maximum flexing at the attachment level was observed on model D2, while the lowest flexing value was found on model E1. When comparing maximum flexing at the mandibular bone level, results similar to model D2 have been shown at the maximum level and model E1 at the minimal level (Table 2).

Discussion

The placement of dental implants in the optimum strategic position can create a favorable abutment situation, allowing for a variety of new prosthetic anchoring options for a removable prosthesis.[17] This treatment modality offers a viable new option, especially for elderly patients with few remaining functional residual teeth located unilaterally in an appropriate position.[18] In addition, this type of surgical intervention frequently represents minimal encumbrance and minimal invasiveness for those patients.[18] Overdentures supported by only a few interforaminal implants could be regarded as a geriatric treatment modality for patients who cannot withstand prolonged oral surgery and for whom financial considerations might dictate the use of a number of implants not sufficient to support a fixed prosthesis.[19] It has been found that convertibility is one of the major advantages of overdentures, where a well-designed complete denture could be converted into an implant-stabilized prosthesis.[20]

Concerning the modeling of the mandibular bone in the FEA study, only the body of the mandible and part of the ramus were modeled based on findings from previous studies, which stated that for comparing the stress distribution around dental implants, a model of the entire mandible is not necessary. In doing this, one has the advantage of reducing modeling and calculation time.[13] In one such study, Teixeira et al mentioned that in a 3D mandibular model, modeling the mandible at distances greater than 4.2 mm mesially or distally from the implant did not result in any significant further yield in FEA accuracy. [21] The challenge was to build the most versatile model possible to accommodate the largest number of variables with the least modifications, so a model with alveolar bone simulation and half of the ramus was simple and adequate compared with modeling the condylar head and coronoid process, which may have presented difficulties and unexpected errors in simulation as well as in the meshing process.

Both animal experiments[22] and various clinical studies[23] have shown that inappropriate loading can cause implant



Model A1

Model A2

Model C1

Model C2

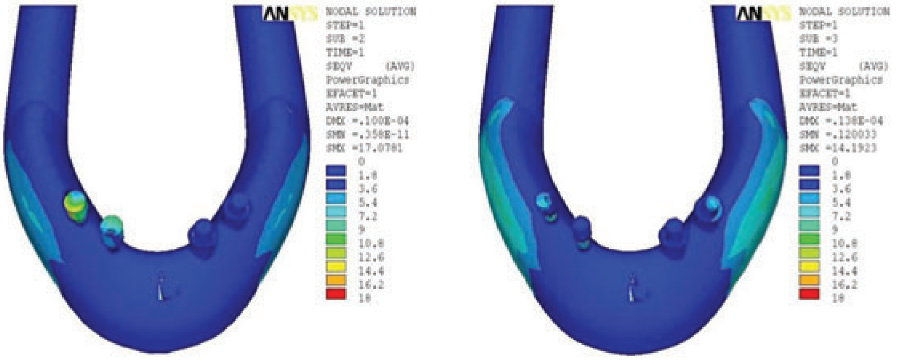
Model E1

Model E2

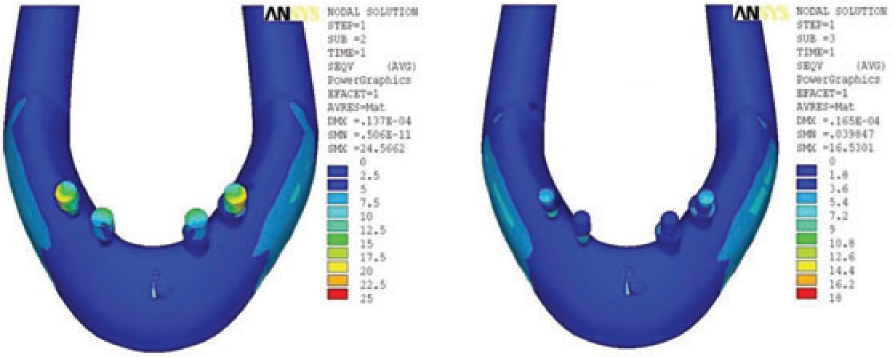
Figure 8 Von Mises stress color contours at attachment level for models A, C, and E. The models were plotted after removing the overdenture and mucosal tissue layers.

failure, especially when connected directly or indirectly to natural teeth. It has been recognized that both implant and bone should be stressed within a certain range for physiologic homeostasis, and that overload can cause bone resorption or fatigue failure of the implant, whereas underloading of the bone may lead to disuse atrophy and subsequent bone loss.[24] Therefore, it is valuable to investigate the stress and strain in the bone and the relation to the different parameters of attachment and overdenture designs, and to correlate the values with a real-world clinical situation to find the clinical implications.

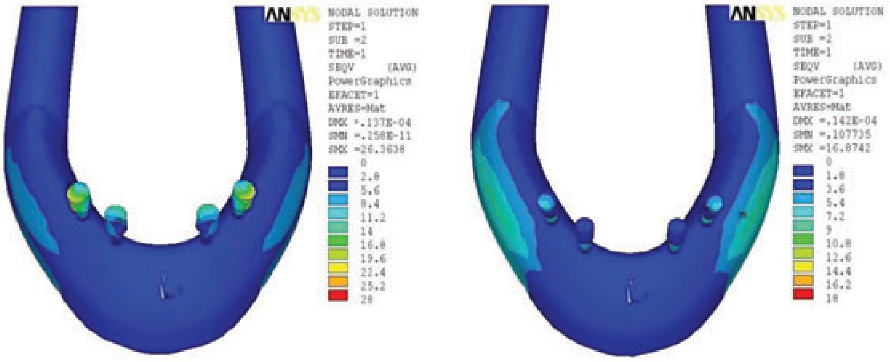
In this study, a comparative evaluation of von Mises stress at the level of the attachment and bone/overdenture support interface was carried out. It was observed that at the attachment level, maximum stress concentrations occurred in model F1 where an overdenture was supported by four freestanding MDIs with O-ring attachments, while minimum von Mises stress values were observed in model E2 with an overdenture supported by three freestanding MDIs with flexible acrylic attachments, and also those models supporting an overdenture with two freestanding MDIs and one natural canine root with either Dalbo



Model B1 **Model B2**



Model D1 **Model D2**



Model F1 **Model F2**

Figure 9 Von Mises stress color contour at attachment level for models B, D, and F. The models were plotted after removing the overdenture and mucosal tissue layers.

Rotex or an MDI screwed in with flexible acrylic attachments (models A2 and C2). Thus, our first null hypothesis was rejected for the reason that the stress-breaking material represented by the flexible acrylic attachments transformed to reduce stress transference from the overdenture to its support foundations[25] and increased the flexing at the attachment level (Table 2). In the case of the O-ring attachments, due to a low modulus of elasticity, the metal-to-metal contact led to the transfer of occlusal forces directly to the body of the MDI, resulting in higher stress levels, while the Dalbo Elliptic attachment also transferred low levels of stress to the Dalbo Rotex retainer screwed into the tooth roots due to the nature of the rubber material and low modulus of elasticity (Table 1, Figs 8, 9).

The second null hypothesis was rejected, as the overdenture supported by three freestanding MDIs transferred minimal stress at attachment and bone level, while four freestanding MDIs supporting an overdenture transferred greater stress than the other models supported by two MDIs and one tooth root.

Table 2 Values of models used

Model	Number of elements	Number of nodal forces	Number of nodal constraints	O'_{VM} on attachments (MPa)	O'_{VM} at the cortical bone-support foundation interface (MPa)	Elastic flexing of attachments (μm)	Elastic flexing of mandible (μm)
Model A1	479,654	112	6114	12.532	10.972	7.83	7.83
Model A2	467,155	112	6114	10.972	8.592	11.4	11.4
Model B1	484,651	112	5520	17.078	14.226	10.0	7.89
Model B2	461,182	112	6090	14.192	9.155	13.8	11.5
Model C1	494,859	112	6114	17.509	10.910	11.3	11.3
Model C2	486,264	112	6114	11.235	10.838	11.5	11.5
Model D1	509,494	112	6090	24.566	14.797	13.7	11.4
Model D2	524,904	112	6162	16.530	7.984	16.5	14.4
Model E1	540,582	112	6498	17.805	14.836	7.34	7.2
Model E2	472,918	112	6114	10.216	7.619	11.4	11.4
Model F1	466,258	112	5964	26.363	14.854	13.7	11.3
Model F2	464,142	112	5964	16.874	10.605	14.2	11.4

The four-MDI design transferred greater stress through the support foundations to the bone because the overdenture support was derived from the support foundation instead of the tissue support. When stress is shared between the overdenture support foundation and the tissue supporting the overdenture fitting surface, minimal stress is observed around the MDI and tooth root as observed in our three-MDI overdenture support designs.

In the case of models A, C, and E with three overdenture supports, the stress distribution was shared between the overdenture support foundations and the residual ridge, and further stress was observed in the posterior body of the mandible. Federick and Caputo[26] offered the explanation that loads applied in a more posterior position result in increased stress transfer to the edentulous ridge by the denture base while simultaneously reducing the load to the implant due to the load transfer characteristics of the evaluated attachments being diminished when the applied load is located in a more posterior position.

In the case of models B, D, and F, which had four overdenture supports regardless of the types of attachments used, the results showed that higher von Mises stress was observed at the distal sites of the second overdenture-supporting foundation bilaterally. This observation substantiates those of Hung and Tsai,[27] Nagasao et al,[28] and Meijer et al,[29] which suggested that high stress values are due to the location of the implants nearest to the loading sites that show the highest stress concentrations. In addition, this posteriorly applied load resulted in an increase in stress delivered to the edentulous ridge by the denture base.

A rigidly anchored MDI, assumed to be 100% osseointegrated, produces a hard overdenture support foundation in comparison to healthy periodontal ligaments supporting natural teeth, which have a cushion-like effect. This explains why the stress contour observed in the attachments supported by natural teeth is always less than that of an MDI-supported attachment. Strain magnitudes around a natural tooth are significantly lower than those of an opposing implant in the contralateral side. The clinical outcomes associated with these problems include bone resorption around the implant neck, bone cracks, and intrusion of any natural teeth. [30,31]

The FEA modeling technique used in this study has limitations when predicting the response of biologic systems to applied loads, as do all modeling systems, including photoelastic modeling, mathematical models, or strain gauge studies.[32] Unlike other in vitro evaluation techniques, the FE method can quantify the physiological strain thresholds of human jawbones. Furthermore, the wide use of in vitro studies including the FE method is due to the fact that in vivo studies cannot be repeated under the same conditions, because of the wide variance of histological structures from one patient to the other.[33] The results of this study may provide a broader understanding about potential stress concentration locations. Long-term clinical research is required to determine the influence of observed stress levels on tissue and prosthesis function.

Conclusions

Within the limitations of this study, the authors' findings revealed that stress can be reduced using flexible acrylic attachments, and further enhancements can be obtained when a triangular overdenture support design is employed. When a three-freestanding MDI system is combined with flexible acrylic attachments, less stress is observed, and this could have clinical implications. A greater amount of flexing and strain was observed in the body of the mandible when flexible acrylic attachments were used to retain the overdenture.

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