Finite element analysis of stress distributions in osteoporotic and normal mandibular dental implant-supported overdentures with magnetic attachments

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Abstract

Purpose: To compare the biomechanical responses of a normal mandible to an osteoporotic mandible with two-implant–supported magnetic attachments. Materials and
Methods: A 3D finite element model of a two-implant–supported mandibular overdenture with magnetic attachments was developed, and normal and osteoporotic bone samples were prepared. Four types of load were applied to the overdenture in each model: 100-N vertical and oblique loads on the right first molar, and 100-N vertical load on the right canine and the incisors. Biomechanical behaviors of the peri-implant bone, implant, and mucosa were recorded. Maximum equivalent stresses and elastic strains were analyzed. Results: Equivalent elastic strain in osteoporotic cortical and cancellous bone was 9% to 71% and, respectively, 142% and 207% greater than in normal cortical bone. Equivalent elastic strain in the first molar oblique loading condition was 101% to 190% greater than in the first molar vertical loading condition. Conclusion: Osteoporotic cancellous bone was weaker and less resistant to deformation than normal bone, and oblique loading was more harmful than vertical loading. *Int J Prosthodont* 2022. doi: 10.11607/ijp.7839

Introduction

With life expectancy continually increasing, edentulism and osteoporosis are becoming more prevalent than ever before[1]. At present, most studies have found that osteoporosis is positively related to tooth loss, and can promote the occurrence and development of periodontitis, which seriously affects the quality of life of patients, and has become the focus of today's health problems[2-4]. The field of prosthodontics has been revolutionized since the advent of osseointegrated titanium implants[5]. In 2002, scholars reached a consensus at the McGill Conference in Canada and announced that traditional dentures are no longer the most appropriate first choice for the restoration of missing dentition (especially the mandible), and implant overdentures as the first choice for patients with edentulous jaws[6].

Overdentures are a minimally invasive and cost-effective option for many edentulous patients, and improved satisfaction can be achieved via stability and retention of the denture[7]. The magnetic attachment is to use magnetic materials to attach the denture to the abutment or implant, and the stability of the denture is further improved by magnetic force. Compared with ordinary attachments, it has less lateral force and is easy
to access, aesthetics and comfort. In addition, it is not restricted by the seat path\textsuperscript{[8]}. Two-
implant-supported overdentures can reportedly yield similar outcomes compared to tooth-
supported overdentures\textsuperscript{[6]}. Dental implant-supported removable prostheses have greatly
improved the oral rehabilitation of edentulous patients\textsuperscript{[9]}.

The level of stress in the bone is related to the dental implant’s design, length, diameter, and crestal module, as well as the quality of the alveolar bone\textsuperscript{[10-12]}. The outcome of dental implantation is closely associated with these factors because adequate engagement of the implant with cortical bone is dependent on initial implant stability\textsuperscript{[13]}. Bone mineral density (BMD) in the alveolar bone of osteoporosis patients is lower than that in normal individuals, and low BMD can affect the success of dental implants\textsuperscript{[14, 15]}. In some clinical studies increased osseointegration times and inadequate bone formation have been associated with the placement of dental implants in low-mineral density bone\textsuperscript{[16, 17]}. In other studies, however, a history of osteoporosis has not been predictive of unfavorable implantation results\textsuperscript{[18-20]}. To date, few studies have investigated the effects of bone quality on stress distributions around dental implants.

At present, the methods commonly used by domestic and foreign scholars to study the biomechanical properties of implanted overdentures include electrical measurement, photoelasticity, and three-dimensional finite element analysis (FEA)\textsuperscript{[21, 22]}. The FEA method is a technique for obtaining a solution to a complex mechanical problem by dividing the problem domain into a collection of much smaller and simpler domains (elements) in which the field variables can be interpolated with the use of shape functions\textsuperscript{[23]}. Since the finite element method was first introduced into stomatology in 1973, it has become an increasingly useful tool for the prediction of the effects of stress on the implant and its surrounding bone\textsuperscript{[24, 25]}. Compared with other methods, the FEA does not require the establishment of a complex entity model, it can easily and quickly
set different materials for the same model and be repeatedly tested and can automatically generate a stress color map by the program to give a complex structure\(^{[26]}\). In this study, biomechanical responses of normal mandible were compared with those of osteoporotic mandible with two implant-supported magnetic attachments via the FEA.

The hypotheses were that, in two-implant-supported magnetic overdentures, (i) deformation of bone adjacent to the implants is greater, and (ii) deformation of bone adjacent to implants is greater under oblique loading than under vertical loading. And the null hypothesis was that there was no statistically significant difference between the deformation of the bone adjacent to the implants in osteoporotic mandibular bone and in normal mandibular bone in two-implant-supported magnetic overdentures.

**Materials and methods**

**Model design**

Finite element (FE) models were developed based on computed tomography (CT) data derived from a 63-year-old female volunteer with a completely edentulous mandible covered by a resin complete denture, which can reveal precise relationships between the denture and mandible. After obtaining informed consent from the patient in accordance with the requirements of the jurisdictional Human Research Ethics Committee (ID #2015EC099), preoperative CT was performed using a KaVo 3D Exam cone beam CT scanner (3D Exam cone beam CT scanner, KaVoDentalGmbH, Bismabring, Germany) and Digital Imaging and Communications in Medicine (DICOM) data were obtained. Three-dimensional image processing of the DICOM data was then performed using Mimics software (Mimics, Version 10.01, Materialise, Leuven, Belgium). Point cloud data derived from the overdenture, cortical bones, and cancellous bones were extracted, and values in Hounsfield units were determined using the threshold value and region
growth function. Modeling software (SolidWorks release 2010, SolidWorks, Massachusetts, U.S.A.) was then used to transform the reference model subject data into the FE solid model of the mandible and overdenture. The 3D geometry (Fig. 1) was exported to ANSYS14.1 FEM preprocessing software (ANSYS, Version 14.1, Canonsburg, Pennsylvania, U.S.A.) and discretized in linear tetrahedral elements. The final model had 258,930 nodes and 125,253 elements.

Cross-sectional viewing of the symmetry plane of the 3D geometry model revealed that the FE models were composed of five parts: overdenture, oral mucosa, cortical bone, cancellous bone, and the combination of the implants and magnetic attachment (Fig. 2). The models of the two implants (4.3 mm in diameter, 10.0 mm in length), (Implant, Nobel Biocare, Gothenburg, Sweden) and the flat type magnetic attachments (MGT5515, Dentium Co., Seoul, Korea) used in this study were designed for implant overdenture. Two implants that were vertically oriented, mutually parallel, and 20 mm away from each other were inserted into the bilateral mandibular canine region. The magnetic attachments (IP-DXFL; Aichi Steel, Aichi-ken, Japan) consisted of a magnet, a keeper, and an abutment cylinder (Fig. 3). Implant and overdenture were also provided with bonded contact, which is non-separating and frictionless\cite{27, 28}.

Material properties and interface conditions

The mechanical properties of the materials are shown in Table 1. The interface between the implants and the bone was assumed to be completely osseointegrated\cite{29}. The implant, keeper, and abutment cylinder was considered to exclude motion between these structures under applied loading\cite{29, 30}. The mandible surface was assumed to be a cortical bone layer
with a uniform width of 2 mm surrounding the cancellous bone surface\textsuperscript{[31]}. Two types of models were created, normal and osteoporotic.

[Table 1 near here]

Based on the precise location between the mandible and the overdenture on CT, the precise geometry of the mucosa in close contact with the inner surface of the denture was obtained\textsuperscript{[32]}. The average thickness of the mucosa covering the edentulous mandible was approximately 2 mm. To simulate a clinical situation in which the overdenture was able to generate rotation and slide on the underlying mucosa in different directions when functioning, sliding friction contact was applied at the overdenture-mucosa interface, and the friction coefficient $\mu$ was set to 0.334\textsuperscript{[31]}.

**Constraints and loading conditions**

The models were restrained at the nodes on the mandible within all directions and all degrees of freedom. To simulate clinical masticatory loading, four types of 100-N loads from different directions and positions were applied to the overdenture: a 100-N vertical load on the lower incisors (VI), a 100-N vertical load on the right canine (VC), a 100-N vertical load on the right first molar (VM), and a 100-N oblique load on the right first molar (OM). The choice of a load of 100-N was based on the premise that both the moderate level of biting force on implant overdentures and the average maximum occlusal force in complete denture patients were approximately 100 N. A 45° angled force was applied buccolingually at the center of the right first molar\textsuperscript{[31]}.

**Results**

**Stress/strain distribution in the peri-implant bone**

The stress/strain areas were distributed around the loading side in the four loading
situations (Fig. 4A, Fig. 4B). In the peri-implant bone, the maximum equivalent stress in the osteoporotic model was lower than that in the normal model, but the maximum equivalent elastic strain was higher. The equivalent elastic strain in osteoporotic cortical bone was 9%–71% greater than that in normal cortical bone. In contrast, the equivalent elastic strain in osteoporotic cancellous bone was 142%–207% greater than that in normal cortical bone. When a vertical load on the right first molar was changed to an oblique load, the maximum equivalent stress and maximum equivalent elastic strain were two to three times greater in the peri-implant bone than in the VM loading condition (Table 2 and Table 3).

Stress/strain distributions in dental implants

In the osteoporotic model the maximum equivalent stress in the dental implant was less than it was in the normal model. The maximum equivalent elastic strains in the two bone conditions did not differ significantly (Fig. 5A, Fig. 5B, Table 4, Table 5).

Stress/strain distributions in the mucosa

In the vertical loading condition, both the maximum equivalent stress and the maximum equivalent elastic strain in the mucosa were similar in the osteoporotic model and the normal model. When an oblique load was applied to the right first molar, however, the maximum equivalent stress and the maximum equivalent elastic strain in the mucosa were
more than 2-fold higher than they were in the VM loading condition (Fig. 6A, Fig 6B).

Discussion

In the restoration treatment of edentulous patients, due to the limitation of the patient's alveolar bone conditions, the retention and stability of the denture have always been the key and difficult problem in the treatment process. Overdentures supported by double implants have the advantages of less trauma, good retention, high chewing efficiency, and low charges\textsuperscript{[33, 34]}. Compared with traditional dentures, they can significantly improve the quality of life of patients\textsuperscript{[35]}. Two-implant-supported overdentures have been considered the gold standard for patients with complete edentulism, and they have exhibited high clinical success rates in patients with normal bone density\textsuperscript{[6]}. Our previous research showed that both cushion-type and dome-type of the magnetic attachments are better choices in two-implant-retained mandibular overdentures\textsuperscript{[36]}, but few studies have investigated stress distributions of implant overdentures in osteoporotic mandibles by far.

The key factors for the success or failure of a dental implant depend on the quantity and quality of the surrounding bone, the type of loading, the bone–implant interface, the length and diameter of the implants, the shape and characteristics of the implant surface, and the prosthesis type\textsuperscript{[37]}. In this study, we mainly discussed the first three factors. Studies suggested that adequate alveolar bone density facilitates the mechanical immobilization of dental implants and there is a close relationship between poor bone quality and implant failure\textsuperscript{[38, 39]}; however, precise relationships between bone
quality and stress distribution remain to be elucidated. A meta-analysis showed sites with poorer bone quality and lack of bone volume may statistically affect implant failure rates\cite{40}. Our study found the similar result that stress is greatly influenced by bone density. Cortical bone has a higher Young’s modulus and is more resistant than cancellous bone. Patra et al.\cite{41} modelled progressive bone loss and partial osseointegration by both 2- and 3-dimensional FEA. When 25%, 75%, and 100% osseointegration was modelled, cortical bone was shown to carry most of the load, with resulting overload leading to crestal bone loss. Stress plots showed that with increasing crestal bone loss, the majority of the load was transferred directly to the weaker trabecular bone tissue\cite{42}. This is one of the reasons why long-term functioning can cause marginal bone resorption.

The equivalent elastic strain in osteoporotic bone is higher than that in normal bone, particularly in osteoporotic cancellous bone. The reason for this is that in osteoporotic bone Young’s modulus and Poisson’s ratio are lower than they are in normal bone. Under the same loading conditions, greater deformation indicates greater micromovement, which is a major reason for failure of implant osseointegration. A meta-analysis reported significantly greater peri-implant marginal bone loss in patients with osteoporosis than that in patients without osteoporosis\cite{43}. Therefore, it is safer to delay the loading of two-implant-supported overdentures with magnetic attachments. Burns et al.\cite{44} reported that a minimum of two implants are required for functional implants supported overdentures, and that the presence of multiple implants can reduce the stress on each individual implant. Thus, adding more implants is a valid option for implant-supported overdentures with magnetic attachments in patients with mandibular osteoporosis.

Besides axial loads, during FEA analysis in the current study, combined loads were also used to apply oblique occlusal force to represent more realistic occlusal
directions. In the right first molar loading position, the oblique loading direction caused a greater maximum equivalent stress than the vertical loading direction. The movement of the denture was represented by the deformation of the mucosa. In the oblique molar loading condition, the mucosa absorbed the stress through more than two times the deformation exhibited in the vertical loading condition. The deformation of the mucosa was primarily concentrated in the distal border seal area. This deformation can compromise border sealing and cause the attachment to loosen. In the current study, load direction had a profound influence on the distribution of stress at the implant bone interface, and oblique loading was more harmful than vertical loading, which is consistent with the findings of Meijer et al\[45\].

Dental implants transfer occlusal force through a prosthesis, sustain masticatory force, and transfer force to the peri-implant bone. In the present study high stress/strain was primarily distributed at the implant bone interface, particularly in the implant neck, which is concordant with previous studies\[46-48\]. However, Nascimento et al.\[49\] used the photoelastic method to study the stress distribution of different types of overdentures, and all attachments showed a similar tension distribution concentrated in the apical third. This may be caused by the structural difference caused by the two modeling methods. In the photoelastic experiment, the implant was directly planted on the epoxy resin model without distinguishing between the cortical bone and the cancellous bone. When using the FEA for analysis, the cortical bone and cancellous bone layer can be set by software, and different elastic moduli can be assigned. Since the elastic modulus of the cortical bone is much greater than that of the cancellous bone, "stress shielding" will occur during the force transmission process\[50\]. The effect of dispersing stress also explains the common clinical phenomenon that bone resorption around implants usually starts from the cortical bone, which reminds us that we should focus on the condition of the implant.
and its surrounding bone in our clinical work, to avoid mechanical complications due to improper force on the implant, and ultimately lead to the failure of implant restoration.

The present study had several limitations. The implants were designed in geometrical shapes without thread. The structures were designed to be isotropic, homogeneous, and linearly elastic, and a 45° oblique force does not fully represent actual masticatory movement. Osseointegration between implants and bone was considered perfect, which is an idealized assumption. However, through the establishment of three-dimensional finite element models of the implant overdentures restored by two attachments and the setting of related mechanical conditions, the qualitative results obtained were still of certain reference value, and the specific used effects still need combined with long-term clinical observation and follow-up. In clinical practice, which the attachment to choose for the final repair should also be comprehensively considered according to the patient’s oral situation and the patient’s subjective requirements.

In conclusion, 1) osteoporosis causes bone deformation, which compromises osseointegration; 2) oblique loads can increase maximum equivalent stress and/or maximum equivalent elastic strain, which may have detrimental effects on implant-supported denture stability; and 3) in osteoporosis patients, it should (is best to) delay the loading of implant-supported overdentures with magnetic attachments.

Acknowledgments

None

Disclosure statement

The authors declare that there are no conflicts of interest regarding the publication of this report.
Data availability statement

The data used to support the findings of this study are included within the article.

References:


### Tables

**Table 1. Material properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Structure</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUM20</td>
<td>Keeper (K)</td>
<td>200,000</td>
<td>0.28</td>
<td>(Kumano et al. 2014)</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>Implant</td>
<td>110,000</td>
<td>0.33</td>
<td>(Sertgoz 1997)</td>
</tr>
<tr>
<td>NdFeB</td>
<td>Magnet (M)</td>
<td>160,000</td>
<td>0.24</td>
<td>(John et al. 2012)</td>
</tr>
<tr>
<td>Pure titanium</td>
<td>Abutment cylinder (A)</td>
<td>117,000</td>
<td>0.30</td>
<td>(Sakaguchi and Borgersen 1995)</td>
</tr>
<tr>
<td>Acrylic resin</td>
<td>Artificial teeth and denture base</td>
<td>8,300</td>
<td>0.28</td>
<td>(Darbar et al. 1995)</td>
</tr>
<tr>
<td></td>
<td>Normal cortical bone</td>
<td>13,700</td>
<td>0.30</td>
<td>(Barbier et al. 1998)</td>
</tr>
<tr>
<td></td>
<td>Normal cancellous bone</td>
<td>1,370</td>
<td>0.30</td>
<td>(Barbier et al. 1998)</td>
</tr>
<tr>
<td></td>
<td>Osteoporotic cortical bone</td>
<td>8,710</td>
<td>0.30</td>
<td>(Polikeit et al. 2003)</td>
</tr>
<tr>
<td></td>
<td>Osteoporotic cancellous bone</td>
<td>465</td>
<td>0.20</td>
<td>(Polikeit et al. 2003)</td>
</tr>
<tr>
<td></td>
<td>Oral mucosa</td>
<td>68</td>
<td>0.45</td>
<td>(Ko et al. 1992)</td>
</tr>
</tbody>
</table>
Table 2. Maximum equivalent stress in the peri-implant bone (MPa)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>N-COB</th>
<th>N-CAB</th>
<th>O-COB</th>
<th>O-CAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>7.07</td>
<td>4.88</td>
<td>0.67</td>
<td>0.65</td>
</tr>
<tr>
<td>VC</td>
<td>10.54</td>
<td>7.77</td>
<td>1.50</td>
<td>1.24</td>
</tr>
<tr>
<td>VM</td>
<td>3.64</td>
<td>2.77</td>
<td>0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>OM</td>
<td>7.20</td>
<td>7.01</td>
<td>0.74</td>
<td>0.71</td>
</tr>
</tbody>
</table>

N-COB, normal cortical bone; N-CAB, normal cancellous bone; O-COB, osteoporotic cortical bone; O-CAB, osteoporotic cancellous bone; VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar.

Table 3. Maximum equivalent elastic strain in the peri-implant bone (10^{-3} \mu m/\mu m)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>N-COB</th>
<th>N-CAB</th>
<th>O-COB</th>
<th>O-CAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>0.52</td>
<td>0.56</td>
<td>0.51</td>
<td>1.49</td>
</tr>
<tr>
<td>VC</td>
<td>0.78</td>
<td>0.90</td>
<td>1.11</td>
<td>2.68</td>
</tr>
<tr>
<td>VM</td>
<td>0.27</td>
<td>0.32</td>
<td>0.20</td>
<td>0.56</td>
</tr>
<tr>
<td>OM</td>
<td>0.54</td>
<td>0.92</td>
<td>0.52</td>
<td>1.59</td>
</tr>
</tbody>
</table>

N-COB, normal cortical bone; N-CAB, normal cancellous bone; O-COB, osteoporotic cortical bone; O-CAB, osteoporotic cancellous bone; VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar.
### Table 4. Maximum equivalent stress in dental implants (MPa)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Normal bone</th>
<th>Osteoporotic bone</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>20.51</td>
<td>16.41</td>
</tr>
<tr>
<td>VC</td>
<td>37.52</td>
<td>30.59</td>
</tr>
<tr>
<td>VM</td>
<td>5.76</td>
<td>4.978</td>
</tr>
<tr>
<td>OM</td>
<td>15.26</td>
<td>14.50</td>
</tr>
</tbody>
</table>

VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar

### Table 5. Maximum equivalent elastic strain in dental implants ($10^{-3}$ µm/µm)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Normal bone</th>
<th>Osteoporotic bone</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>VC</td>
<td>0.34</td>
<td>0.28</td>
</tr>
<tr>
<td>VM</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>OM</td>
<td>0.14</td>
<td>0.13</td>
</tr>
</tbody>
</table>

VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar
### Table 6. Maximum equivalent stress in the mucosa (MPa)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Normal bone</th>
<th>Osteoporotic bone</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>1.99</td>
<td>1.96</td>
</tr>
<tr>
<td>VC</td>
<td>1.05</td>
<td>0.99</td>
</tr>
<tr>
<td>VM</td>
<td>0.68</td>
<td>0.62</td>
</tr>
<tr>
<td>OM</td>
<td>1.62</td>
<td>1.67</td>
</tr>
</tbody>
</table>

VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar

### Table 7. Maximum equivalent elastic strain in the mucosa (10^{-3} \mu m/\mu m)

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Normal bone</th>
<th>Osteoporotic bone</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>2.96</td>
<td>2.91</td>
</tr>
<tr>
<td>VC</td>
<td>1.68</td>
<td>1.57</td>
</tr>
<tr>
<td>VM</td>
<td>1.01</td>
<td>0.92</td>
</tr>
<tr>
<td>OM</td>
<td>2.47</td>
<td>2.60</td>
</tr>
</tbody>
</table>

VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar
Figure 1: Three-dimensional solid geometric models of the mandible, mucosa, overdenture, implants, and magnetic attachments
Figure 2: Cross-sectional view of the symmetry plane of the three-dimensional geometry model, depicting the overdenture (O), mucosa (M), magnetic attachment (CM), cancellous bone (CAB), and cortical bone (COB)
Figure 3: Combination models of the implants and magnetic attachments. The keeper (K) is screwed onto the abutment cylinder (A) and inserted into the implant, and the magnet (M) is assembled in the denture.
Figure 4A Maximum equivalent stress in the peri-implant bone under four loading conditions (MPa). Colors indicate levels of stress/strain from lowest (dark blue) to highest (red). N-COB, normal cortical bone; N-CAB, normal cancellous bone; O-COB, osteoporotic cortical bone; O-CAB, osteoporotic cancellous bone; VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar.
Figure 4B Maximum equivalent elastic strain in the peri-implant bone under four loading conditions. Colors indicate levels of stress/strain from lowest (dark blue) to highest (red). N-COB, normal cortical bone; N-CAB, normal cancellous bone; O-COB, osteoporotic cortical bone; O-CAB, osteoporotic cancellous bone; VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar.
Figure 5: Stress/strain distribution in dental implants. (A) Maximum equivalent stress in the dental implant under four loading conditions (MPa). (B) Maximum equivalent elastic strain in the dental implant under four loading conditions. Colors indicate levels of stress/strain from lowest (dark blue) to highest (red). VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar.
Figure 6

Figure 6: Stress/strain distribution in the mucosa. (A) Maximum equivalent stress in the dental implant under four loading conditions (MPa). (B) Maximum equivalent elastic strain in the dental implant under four loading conditions. Colors indicate levels of stress/strain from lowest (dark blue) to highest (red). VI, 100-N vertical load on the lower incisors; VC, 100-N vertical load on the right canine; VM, 100-N vertical load on the right first molar; OM, 100-N oblique load on the right first molar.