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Influence of implant number on the biomechanical behaviour of mandibular implant-retained/supported overdentures: A three-dimensional finite element analysis

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ABSTRACT

Objective: The aim of this study was to evaluate strain distribution in peri-implant bone, stress in the abutments and denture stability of mandibular overdentures anchored by different numbers of implants under different loading conditions, through three-dimensional finite element analysis (3D FEA).

Methods: Four 3D finite element models of mandibular overdentures were established, using between one and four Straumann implants with Locator attachments. Three types of load were applied to the overdenture in each model: 100 N vertical and inclined loads on the left first molar and a 100 N vertical load on the lower incisors. The biomechanical behaviours of peri-implant bone, implants, abutments and overdentures were recorded.

Results: Under vertical load on the lower incisors, the single-implant overdenture rotated over the implant from side to side, and no obvious increase of strain was found in peri-implant bone. Under the same loading conditions, the two-implant-retained overdenture showed more apparent rotation around the fulcrum line passing through the two implants, and the maximum equivalent stress in the abutments was higher than in the other models. In the three-implant-supported overdenture, no strain concentration was found in cortical bone around the middle implant under three loading conditions.

Conclusions and clinical significance: Single-implant-retained mandibular overdentures do not show damaging strain concentration in the bone around the only implant and may be a cost-effective treatment option for edentulous patients. A third implant can be placed between the original two when patients rehabilitated by two-implant overdentures report constant and obvious denture rotation around the fulcrum line.

1. Introduction

In recent years, the treatment of a fully edentulous mandible by means of an implant overdenture has become a routine strategy.[1–3] Completely edentulous patients who have persistent problems using conventional mandibular prostheses can benefit significantly from implant overdentures.[4]

In 2002, the McGill consensus statement suggested that an overdenture retained by two implants should be the first

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choice of treatment for the edentulous mandible.[5] Recently, there have been reports suggesting that a single implant is adequate for overdenture retention and can result in a high success rate comparable to overdentures supported by multiple implants.[6–11] Walton et al. compared patient satisfaction and prosthetic outcome for mandibular overdentures retained by one or two implants in 86 participants for one year. In this randomized clinical trial, researchers found lower component costs and treatment times, with comparable satisfaction and maintenance time, for overdentures retained by a single midline implant.[8] However, some authors have reported unexpectedly high failure rates for single-implant retained mandibular overdentures using an immediate loading protocol.[12,13]

Other researchers have investigated mandibular overdentures using three or four implants. Theoretically, the application of three or four implants creates an angular relationship between the implants instead of a straight-line relationship. In the three-implant-supported overdenture, the most anteriorly positioned implant may provide indirect retention for the denture by preventing the intrusion of the anterior portion of the denture towards the tissues.[14] Therefore, it has been recommended by some authors that clinicians should use three or four implants in situations that require increased retention, such as high muscle attachment or prominent mylohyoid ridges.[15] However, in general, the use of mandibular overdentures supported by more than two implants does not lead to greater patient satisfaction in terms of denture and social function. Meijer et al. found no clear difference in either clinical or radiographic outcomes between two-implant-retained and four-implant-supported mandibular overdentures over a 10-year evaluation period.[16] Mericske-Stern compared the clinical results between two-, three- and four-implant mandibular overdentures and proposed that two implants can adequately serve as retention for a complete mandibular denture.[17] For reasons of cost-effectiveness, Meijer et al. proposed that a two-implant overdenture is advisable for patients with Cawood classes IV–VI resorption of the mandible and complaints concerning retention and stability of the lower denture.[16]

Besides retention, it is also of vital importance not to cause excessive load on implants.[18] In natural teeth, the periodontal ligament acts as an intermediate cushion to buffer the occlusal loads.[19] However, in the osseointegrated dental implant, occlusal loads are transmitted directly to the surrounding bones. When overloading happens, high deformations (above 2000–3000 microstrain) occur in the bone around the implants. When pathological overloading occurs (over 4000 microstrain), stress and strain gradients exceed the physiological limits of the bone, which may cause micro-fractures at the bone–implant interface, fracture of the implant, loosening of components of the implant system, and unwanted bone resorption.[20,21]

Recognizing the damage done by overloading, clinicians pay close attention to the stress and strain developed in peri-implant bone when using different prosthetic designs. Three-dimensional finite element analysis (3D FEA) has been considered a precise and appropriate approach for investigating stress and strain distribution in bone and offers many advantages over other methods in simulating the complexity of clinical situations.[22] To date, there has been little previous research comparing the stress or strain in peri-implant bone using mandibular overdentures retained by different numbers of implants. Therefore, the main goal of this study was to compare through 3D FEA the strain distributions in peri-implant bone, stress in the abutments and denture stability of mandibular overdentures retained by one, two, three, or four implants.

2. Materials and methods

2.1. Model design

To obtain the geometry of a totally edentulous patient's mandible, a computed tomography (CT) examination was carried out on a volunteer, with approval from the ethnical committee of Peking University School of Stomatology (IRB00001052-07051). Her mandible and mandibular overdenture were scanned. The CT examination files were then imported into Mimics8.0 (Materialise, Leuven, Belgium). Straumann implants (Straumann, Basel, Switzerland; diameter: 4.1 mm, length: 10 mm, screw-shaped) and Locator attachment systems (Zest Anchors, Escondido, CA, USA; diameter: 3.85 mm, length: 3.85 mm) were chosen as overdenture retainers for this biomechanical analysis. The three-dimensional geometries of the edentulous mandible and prosthetic components were modelled in SolidWorks 2008 (SolidWorks Corporation, Vélizy-Villacoublay, France).

The geometries of the mandible, overdenture, implant and attachment systems were then meshed using Abaqus 6.8 (Simulia Corporation, Vélizy-Villacoublay, France). Four 3D FE models of an edentulous mandible supporting an implant overdenture were designed (Fig. 1), each with different numbers of implants in the anterior area of mandible between the mental foramina. All implants were vertically positioned and well distributed in the interforaminal region, at least 6 mm mesial to the mental foramen, as follows:

- Model A, a single implant was located in the midline of the jaw.
- Model B, the overdenture was retained by two implants 20 mm apart.
- Model C, the overdenture was retained by three implants with the central one in the midline of the jaw and other two a distance of 18 mm to either side.
- Model D, the overdenture was retained by four implants 12 mm apart.

The models were meshed with 3D four-node tetrahedron elements. The total numbers of elements and nodes are listed in Table 1. A refined mesh was generated in the interforaminal region to faithfully reproduce the complex strain distribution observed in peri-implant bone.

2.2. Material properties

The edentulous jaw was composed of a 2-mm constant cortical bone layer around a cancellous bone core, covered by a 2-mm thick mucosa. The Locator attachment system was composed of three parts: abutment, nylon replacement male

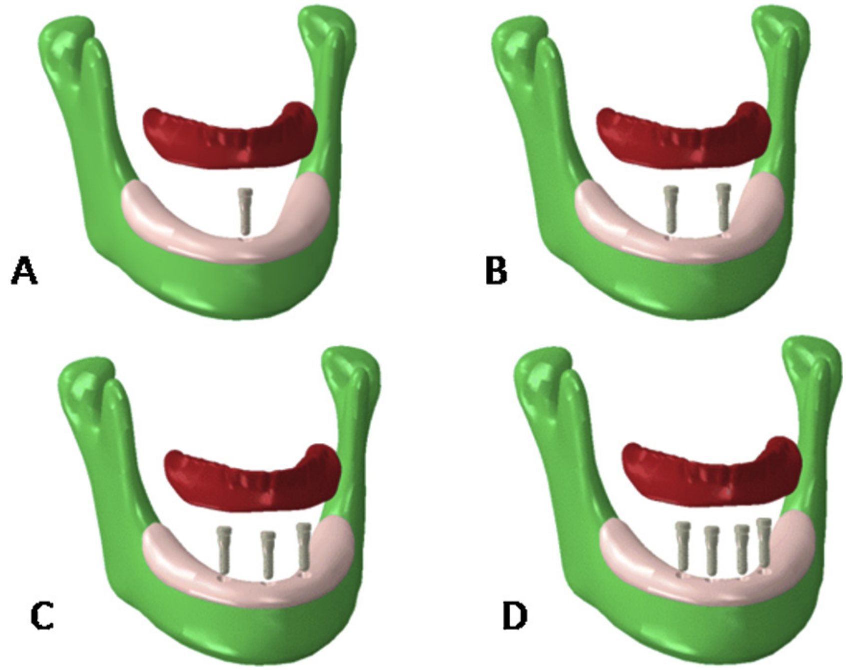

Fig. 1 – The four 3D finite element models of the edentulous mandible and prosthetic components: (A) represents model A (single-implant model); (B) represents model B (two-implant model); (C) represents model C (three-implant model); and (D) represents model D (four-implant model).

and titanium cap. The abutment and cap were made of Ti6Al4V titanium alloy, as was the implant. The material properties of the cortical and cancellous bone, mucosa and prosthetic components were determined from values obtained from the literature (Table 2). All materials were assumed to be isotropic, homogeneous and linearly elastic.

2.3. *Contact management and loading conditions*

Implants were considered totally osseointegrated. Therefore, a mechanically perfect interface was presumed to exist between implant and bone. However, the interface between the overdenture and the mucosa was not fixed when functioning. Instead, the overdenture was able to rotate and slide on the mucosa in different directions. To simulate this displacement, we assumed that sliding friction existed between the overdenture and mucosa. The coefficient of sliding friction between the overdenture and mucosa was set to be 0.334 in accordance with previous experiments carried out by our team.[27]

The models were constrained at the nodes on the mesial and distal bone in all degrees of freedom. Three types of load were applied to the overdenture in each model to simulate functional loading, namely 100 N vertical and inclined loads on the left first molar and 100 N vertical load on the lower incisors. To facilitate discussion, the three loading conditions have been abbreviated as VM, IM and VI for vertical load on the left first molar, inclined load on the left first molar and vertical load on the lower incisors, respectively. IM refers to a 45-° angled force buccolingually applied at the centre of the left first molar.

Table 1 – Total number of elements and nodes.

	Elements	Nodes
Model A	115,100	7080
Model B	200,741	50,233
Model C	273,726	67,399
Model D	404,019	96,916

Table 2 – Material properties.

	Young's modulus (MPa)	Poisson's ratio	Reference
Ti-6Al-4V	103,400	0.35	Sertgöz and Güvener[23]
Cortical bone	13,700	0.3	Barbier et al.[24]
Cancellous bone	1370	0.3	Barbier et al.[24]
Overdenture	4500	0.35	Brunski et al.[25]
Mucosa	1	0.37	Menicucci et al.[26]
Nylon	28.3	0.4	Manufacture

3. Results

3.1. *Strain distribution in peri-implant cortical bone*

Maximum equivalent strains in the cortical bone around implant under three types of load for each model is shown in Table 3. Strain distributions in the peri-implant cortical bone of each model under three loading conditions are illustrated in Figs. 2–5. Under all three loading conditions, the maximum strain values were below 2500 $\mu\varepsilon$ in all models. In models A, C and D, the peak strain values in the cortical bone showed an increasing trend as the number of implants increased, and the

Table 3 – Maximum equivalent strains in peri-implant cortical bone under three loading conditions (με).

Loading condition	Model A	Model B	Model C	Model D
VM	474.5	535.9	843.3	835.4
IM	1320	1180	1609	2082
VI	606.6	1340	992.3	1323

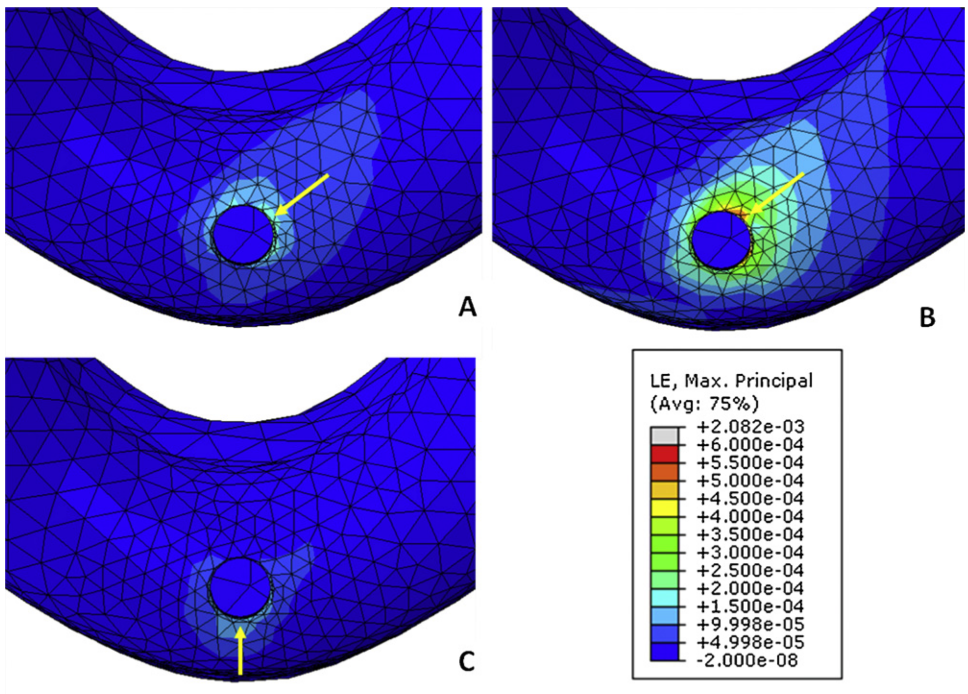

Fig. 2 – Equivalent strain distribution in the cortical bone of model A under three loading conditions ((A) VM, (B) IM and (C) VI). Colours indicate level of strain from dark blue (lowest) to red (highest). The arrows show the sites at which peak strain values occur.

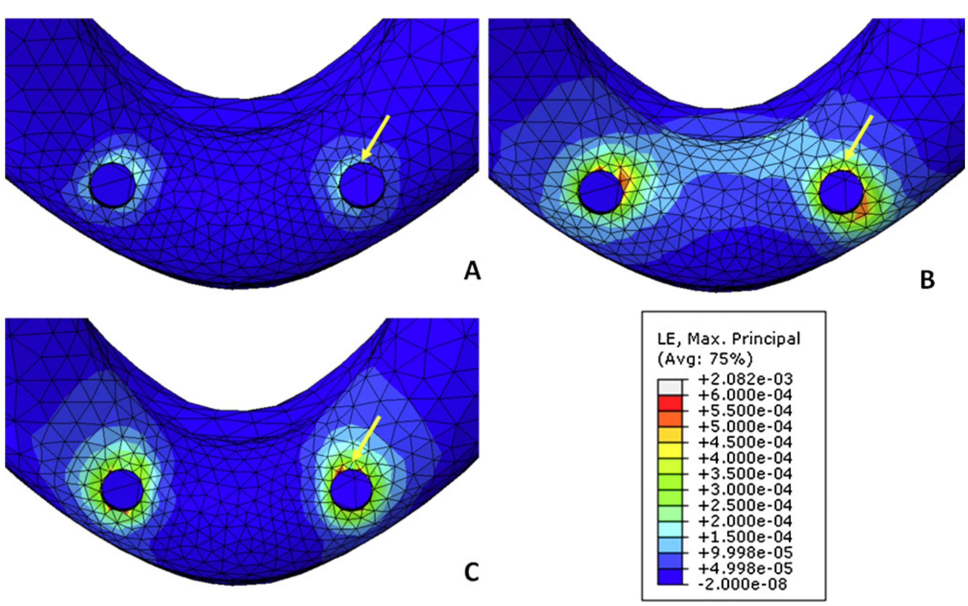

Fig. 3 – Equivalent strain distribution in the cortical bone of model B under three loading conditions ((A) VM, (B) IM and (C) VI). Colours indicate level of strain from dark blue (lowest) to red (highest). The arrows show the sites at which peak strain values occur.

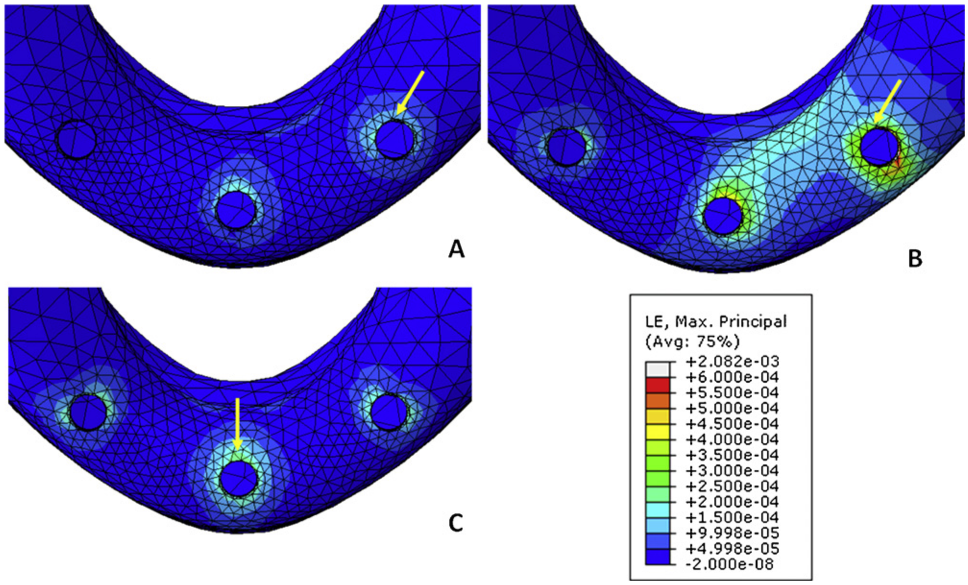

Fig. 4 – Equivalent strain distribution in the cortical bone of model C under three loading conditions ((A) VM, (B) IM and (C) VI). Colours indicate level of strain from dark blue (lowest) to red (highest). The arrows show the sites at which peak strain values occur.

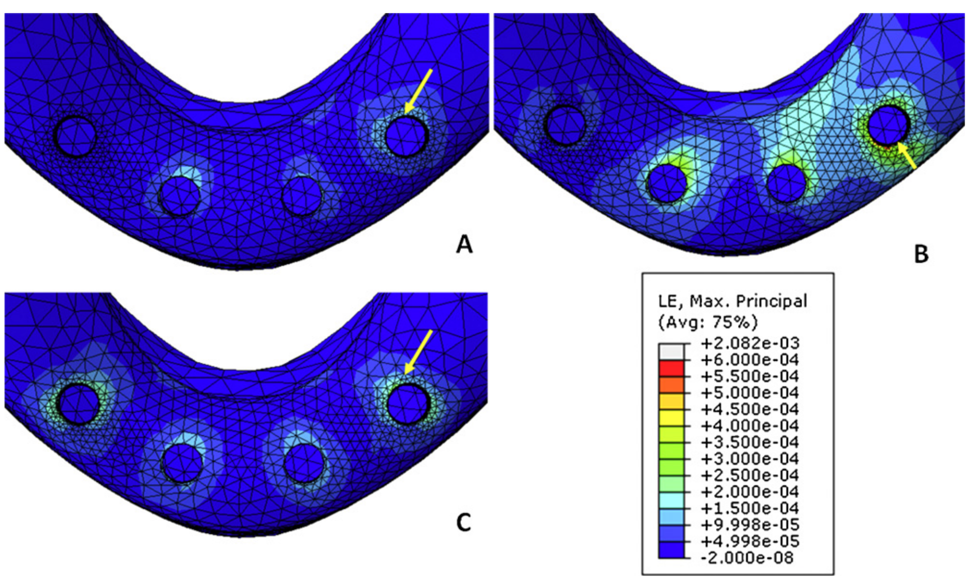

Fig. 5 – Equivalent strain distribution in the cortical bone of model D under three loading conditions ((A) VM, (B) IM and (C) VI). Colours indicate level of strain from dark blue (lowest) to red (highest). The arrows show the sites at which peak strain values occur.

maximum strain values in peri-implant bone under IM were higher than under VM or VI. However, under VI, the maximum strain value in model B was as high as that in model D, and was located on the lingual side of the peri-implant cortical bone (Fig. 3C). When model D was loaded on the incisors, the peak strain values in the cortical bone were found to be concentrated around the distal two implants (Fig. 5C), and were nearly three times higher than those around the central two implants.

3.2. *Stress in abutments*

The maximum equivalent stress values in the abutments under three loading conditions in each model are shown in Table 4. It was notable that under VI, the maximum stress value in model B was about three times as high as in the other models and was located on the labial side of the interface between the abutment and the nylon replacement.

Table 4 – Maximum equivalent stresses in abutments under three loading conditions (MPa).

Loading condition	Model A	Model B	Model C	Model D
VM	13.62	20.1	21.14	21.46
IM	17.03	23.59	29.05	28.32
VI	15.41	76.57	26.33	21.13

Table 5 – Maximum pressure on mucosa under three loading conditions (MPa).

Loading condition	Model A	Model B	Model C	Model D
VM	0.2641	0.3268	0.2753	0.2474
IM	0.2544	0.3462	0.2835	0.2454
VI	0.1984	0.4529	0.2266	0.2095

Table 6 – Contact area between the denture and mucosa under three loading conditions (mm^2).

Loading condition	Model A	Model B	Model C	Model D
VM	861.9	1183	1128	1099
IM	1044	1125	1041	992.4
VI	793.4	200.4	303.7	236.3

3.3. *Pressure on the mucosa and the contact area between the denture and the mucosa*

Tables 5 and 6 show the maximum pressure on the mucosa and the contact area between the denture and mucosa respectively. Under all three loading conditions, the maximum pressure on the mucosa in model B was higher than in the other models, especially under VI. The peak pressure in model B was observed under VI; it was approximately two times as high as in the other three models, and was concentrated between the labial side of the anterior alveolar ridge and the denture.

Under VM and IM, the contact area between the denture and mucosa was larger than that under VI. Under VM, the contact area between the denture and mucosa in model A was about 75% of the area in the other models. Under VI, the contact between the denture and mucosa mainly took place on the labial side of the anterior alveolar ridge for models B–D, whereas for model A it was concentrated on the left side of the whole alveolar ridge (Fig. 6). The contact area in model A was

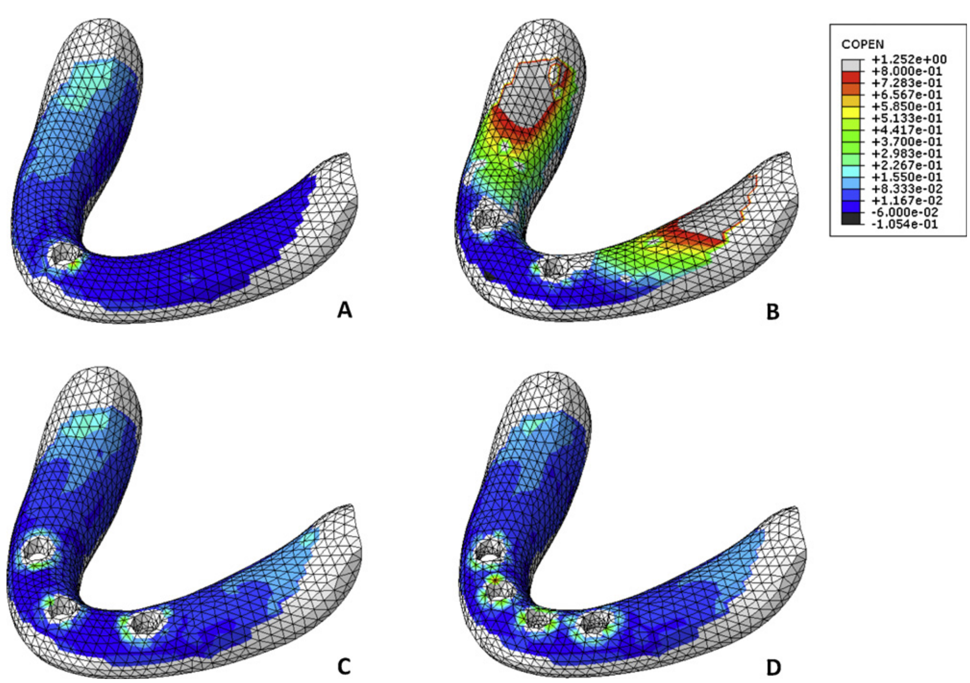

Fig. 6 – Distribution of contact area between the denture and mucosa under a VI load. (A–D) represent models A–D, respectively. The cold tone represents the area where contact with the denture was close and tight, whereas the warm tone indicates the area where the denture tilted and separated from the mucosa.

about three times as large as in the other three models under VI. This illustrates that, when functioning with the anterior teeth, the single-implant-retained overdenture rotated over the implant from one side to the other.

4. Discussion

The FE models used in the present study allows representation of a more detailed and complex geometry. However, the inherent limitations of the FEA with regards to strain distribution should always be taken into consideration.[22,23] The models used deviated in many aspects from a clinical situation. The structures in the models were all assumed to be homogeneous, isotropic and linearly elastic. However, it is well documented that the cortical bone of the jaw is transversely isotropic and inhomogeneous. In addition, a 100% implant/bone interface was established, which does not match clinical situations. Thus, the results of FEA of a problem like this should be interpreted with some care. The absolute values of the different strains obtained in this study are of minor interest. What are of interest are the relative values of the different strains for the different implant overdenture designs. Therefore, the results we obtained should be considered as a reference to choose between different overdenture designs in the clinical treatment. Prospective clinical studies are required to verify the results.

In previous studies, the interface between the denture and the mucosa was assumed to be fixed to facilitate modelling and calculations.[28,29] However, our study assumed that sliding friction existed between the denture and the mucosa. Our model of overdenture could therefore rotate and slide on the mucosa in various directions when functioning and so could more accurately simulate actual denture movement in daily use. In addition, we assumed in the present study that, with regard to posterior loads, the opposite side would show the same mechanical behaviour as the loaded side.

The results from our study indicated that in all models, maximum equivalent strains in peri-implant bone under all three loading conditions were below 2500 $\mu\varepsilon$, and were therefore lower than the physiological tolerance threshold of bone.[21] This findings agrees with previous clinical studies that showed no significant difference in peri-implant bone resorption between single-, two- and four-implant-retained/supported overdentures, indicating that the strain in the bone around implants was within the physiological threshold, having little effect on the implant survival rate.[11,16,30]

Clinicians anticipated that with an increase in implant number, the maximum strain value in peri-implant bone would decrease and the strain in the bone would be more widely distributed. This was based on the assumption that when adding more implants for anchorage and support, the force borne by each implant would decrease, resulting in a decrease of strain in the bone. Nevertheless, according to our results, the peak strain value in peri-implant bone increased with the increase in number of implants in models A, C and D under three loading conditions. This can be explained by the increase in the supporting effect of the implants. In the single-implant overdenture, most of the force was loaded on the mucosal area. With increased implant numbers, more of the chewing force was shared by the implants while less was borne by the mucosa, resulting in the increased peak strain values in cortical bone around the implants. This is also the reason why single- and two-implant overdentures are called ''implant-retained overdentures'', while overdentures on four implants are called ''implant-supported overdentures''.

Our study showed that under VI, which simulated the action of cutting food with the anterior teeth, the maximum stress value in the abutments in model B was three times higher than in the other three models, suggesting that possible damage to the abutments might happen more easily in two-implant overdentures than single, three and four-implant overdentures. Kimoto et al. also reported rotational movement around the fulcrum line between the two implants in some of their edentulous patients rehabilitated using two-implant-retained overdentures.[31] However, due to the scarcity of literature concerning the effects of implant number on stress distribution in the upper structure of the overdenture, further experimental stress analysis and long-term clinical research needs to be carried out.

It can be postulated that forces, both axial and lateral, generated by an overdenture on a single implant, have the potential to be greater than those produced by a multiple implant-retained/supported overdenture, resulting in a risk of loss of osseointegration. However, Maeda et al. evaluated the biomechanical rationale for single-implant mandibular overdentures using magnetic and ball attachments in an *in vitro* model and found that single-implant overdentures had biomechanical properties similar to two-implant overdentures in terms of lateral forces to the abutment and denture base movements under functional molar loads.[32] Our study showed that stress in the abutment of model A was lower than in the other three models under three loading conditions. Moreover, when functioning with anterior teeth, the overdenture anchored by a single implant rotated over the implant from one side to another and randomly inclined to one side, which in our case happened to be the left side. A similar effect happened under VM with the same model. Thus, the left side of the whole alveolar ridge took the role of bearing the occlusal load. The contact area between the denture and mucosa in model A was therefore much larger than in the other three models, causing less pressure on the mucosa. In addition, under VI, the maximum equivalent strain in peri-implant cortical bone in model A was much lower than in the other three models, indicating that denture loading did not cause any apparent increase of strain in peri-implant bone and that the implant mainly took the role of retention rather than support. Therefore, our results suggest that use of a single-implant overdenture does not lead to strain concentration in the bone around the implant and could be a feasible choice for edentulous patients. Clinical studies also suggest that mandibular single-implant overdentures are a successful and beneficial treatment option for older edentulous adults with minimal financial outlay.[6–11]

Two-implant overdenture has been considered a first choice for the treatment of edentulous patients worldwide. However, we found that under anterior loading, the denture showed more obvious rotation than it did in models C or D. This agrees with another study showing that the application of three or four implants may create an angular instead of a straight-line relationship between the implants, preventing the intrusion of the anterior portion of the denture tissueward.[14] Clinical studies have also suggested that one of the chief concerns of patients wearing two-implant overdentures is denture rotation.[31] Therefore, it has been recommended by some investigators that clinicians should use three or four implants when increased retention is required.[15] Clinicians should also pay attention to the appropriate extension of the denture base and occlusal harmony to prevent excessive rotational movement.[31]

There has been some concern that with three-implant overdentures, the strain in the bone around the middle implant may be high, especially when functioning with the posterior teeth. Nevertheless, our results showed that during simulation of grinding food with the posterior teeth, the maximum equivalent strain in the cortical bone was located around the left implant, on the same side as the load. Therefore, it could be concluded from our results that overdenture anchored by three implants did not cause any strain burden in the cortical bone around the middle implant. Geckili et al. also found that the marginal bone loss around the central implants of three-implant mandibular overdentures, when using ball or bar attachments, was lower than around the implants on the left and right sides.[33] Furthermore, as mentioned above, three-implant overdenture was more stable than the two-implant model in our study. For patients who complain about rotational movement around the fulcrum line of their two-implant mandibular overdenture, adding a third implant in the midline of the jaw could theoretically improve denture stability.

5. Conclusion

Within the limitations of this *in vitro* study, the following conclusions can be drawn:

- The maximum strain values in peri-implant bone were within physiological limits in all four models.
- The single-implant model demonstrated the features of low strain in peri-implant bone, low stress in the abutments and compromised denture stability. It provides a cost-effective treatment alternative for patients with limited economic resources.
- When simulating the action of cutting food with the anterior teeth, the two-implant model demonstrated relatively high strain in peri-implant bone, high stress in the abutments and compromised denture stability. A third implant placed between the original two could provide a possible solution when patients rehabilitated using two-implant overdentures report constant and obvious denture rotation around the fulcrum line.
- When functioning with the anterior teeth, three- and four-implant models were steadier than the two-implant model. No strain burden was found in the cortical bone around the middle implant in the three-implant model.

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