Albahit Journal of Applied Sciences
"open-access, peer-reviewed biannual journal"
eISSN: 2708-8936, pISSN: 2708-244X
Volume 5, Issue 2, 2026
Page No: 92-103
***Website**: https://albahitjas.com.ly/index.php/albahit/en/index*

Effect of Implant Design and Marginal Bone Loss on Biomechanical Stress Patterns: A 3D Finite Element Study

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Received: 15-02-2026 | **Accepted:** 25-04-2026 | **Published:** 02-05-2026

Abstract:
This study investigates the biomechanical behavior of three dental implant geometries—solid rover, hollow rover, and cylindrical threaded designs—under simulated masticatory loading using three-dimensional finite element analysis. vertical ($0 < FV < 2500$ N) and lateral ($0 < FL < 500$ N) loads applied on the vertical axis of the implant, and bending moments ($0 < M < 4000$ N.mm forces were applied to evaluate stress distribution in cortical and trabecular bone surrounding anterior implants. The analysis revealed that marginal bone loss significantly increases stress concentration, particularly in cortical regions. Among the tested designs, hollow rover implants demonstrated more balanced stress profiles in trabecular bone, though potentially at the expense of mechanical resistance. These findings suggest that implant geometry and bone integrity must be carefully considered to optimize biomechanical performance and clinical outcomes.

Keywords: Biomechanics, Bone, Finite element analysis, optimal geometry design.

تأثير تصميم الغرسة وفقدان العظم الهامشي على أنماط الإجهاد الميكانيكي الحيوي: دراسة ثلاثية الأبعاد باستخدام طريقة العناصر المحددة

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الملخص
تهدف هذه الدراسة إلى استقصاء السلوك الميكانيكي الحيوي لثلاثة أشكال هندسية من غرسات الأسنان، وهي: الغرسة الصلبة من نوعRover ، والغرسة المجوفة من نوعRover ، والغرسة الأسطوانية الملولبة، وذلك تحت أحمال مضغ محاكاة باستخدام التحليل ثلاثي الأبعاد بالعناصر المحددة.(Finite Element Analysis)

تم تطبيق أحمال عمودية ($0 < F_V < 2500$ N) وأحمال جانبية ($0 < F_L < 500$ N) على المحور الرأسي للغرسة، بالإضافة إلى عزوم انحناء ($0 < M < 4000$ N\cdotpmm) ، وذلك لتقييم توزيع الإجهادات في العظم القشري والعظم الإسفنجي المحيطين بالغرسات الأمامية.

أظهرت نتائج التحليل أن فقدان العظم الهامشي يؤدي إلى زيادة ملحوظة في تركّز الإجهادات، خاصة في مناطق العظم القشري. ومن بين التصاميم المدروسة، أظهرت الغرسات المجوفة من نوع Rover توزيعاً أكثر توازناً للإجهادات داخل العظم الإسفنجي، وإن كان ذلك قد يكون على حساب المقاومة الميكانيكية للغرسة.

تشير هذه النتائج إلى أن هندسة الغرسة وسلامة البنية العظمية المحيطة بها يجب أن تؤخذا بعين الاعتبار بعناية عند تصميم الغرسات السنية، بهدف تحسين الأداء الميكانيكي الحيوي والنتائج السريرية.

الكلمات المفتاحية: الميكانيكا الحيوية، العظم، تحليل العناصر المحددة، التصميم الهندسي الأمثل.

1. Introduction

The hypothesis that motivates this study is: "Does alternative dental component design reduce the level of stress shielding of the jawbone during the implant placement process and at the same time relieve the satisfactory load on the intraosseous integrated dental implants? In all cases of functional loading with implants, occlusal forces are transferred to the bone-implant interface via the implant-supported prosthesis [1, 2].. The process of force transmission to the supporting bone and its consequences depend on the nature of the applied force (amplitude, direction, frequency), the design of the implant (shape, length, diameter), the biological properties of the bone-implant interface, and the response of the bone tissue to the mechanical environment created by the implant loading. To date, several implant design factors have been recognized and proposed in the literature that affect the force transfer characteristics to the surrounding bone; Albrektsson et al. Showed that there is a greater bone loss around cylinder-type implants compared to screw-type implants [3, 4]..

Limbal bone loss around oral implants is inevitable with the implant systems currently in use [5]. Limbal bone loss due to biological causes has been clearly demonstrated in animal studies [6, 7, 8]. The influence of bacterial pathways on the development of peri-implant infection has also been studied [9].

However, conclusions about the limbal bone response to loading have not yet been drawn, as there is evidence of bone loss [10, 11, 12] or lack thereof [13, 14, 15, 16] in bite overload experiments in animals. Similar discrepancies exist in the assessment of clinical outcomes [17, 18]. Therefore, more specific studies are needed to identify and quantify the biomechanical factors leading to time-dependent limbal bone loss. Modeling is not only an important factor in bone growth during growth itself, but also probably effectively modulates bone structure and bone mass when the mechanical environment changes.

This may explain why a stable level of marginal bone has been found around implants subjected to occlusal overload [19, 20,]. As bone quality declines in adult humans, there is a constant remodeling of bone to maintain its suitability at a biomechanical level. Therefore, during the remodeling process, trabecular bone is perforated and removed, and cortical bone increases porosity and decreases the width of the cortical layer. In addition, the natural turnover of bone is disrupted and preparing the implant site may even be difficult. Changes in the mechanical environment of peri-implant bone are associated with different occlusal loading protocols. Therefore, minimal effective stresses on a prematurely mineralized area of implant bone may have pathological consequences. In this respect, the claim of limbal bone loss due to loading is valid. In general, scientific evidence suggests that the bone level relative to the implant neck stabilizes to a certain level due to the physiological interaction of mechanical and biological factors.

Therefore, this study aims to evaluate whether alternative dental implant geometries—specifically solid rover, hollow rover, and threaded cylindrical designs—can reduce stress shielding and optimize load transfer to the peri-implant bone. Using three-dimensional finite element analysis, we simulate functional loading scenarios to quantify stress distribution patterns and assess the biomechanical implications of progressive marginal bone loss in anterior implant regions.

Geometry modeling and materials

Using finite element analysis (FEA), Rieger et al. Showed that tapered implants were superior to cylindrical implants in order to avoid punching stresses and as a choice of retention element [2].

This study explores the hypothesis that through redesign, a dental implant prosthesis can be developed that significantly reduces stress shielding and mitigates the effects of masticatory loading. The description of the development of a new prosthetic designed to treat this problem through a new fixation geometry is based on static loading and finite element analysis. Therefore, as shown in Figure (1), three structurally similar but morphologically different types of implants are compared: threaded cylindrical implants, spherical leaf implants (solid rover implants), and hollow rover implants to understand the stress behavior and implant/ mathematical model to understand the stress distribution along the bone surface.

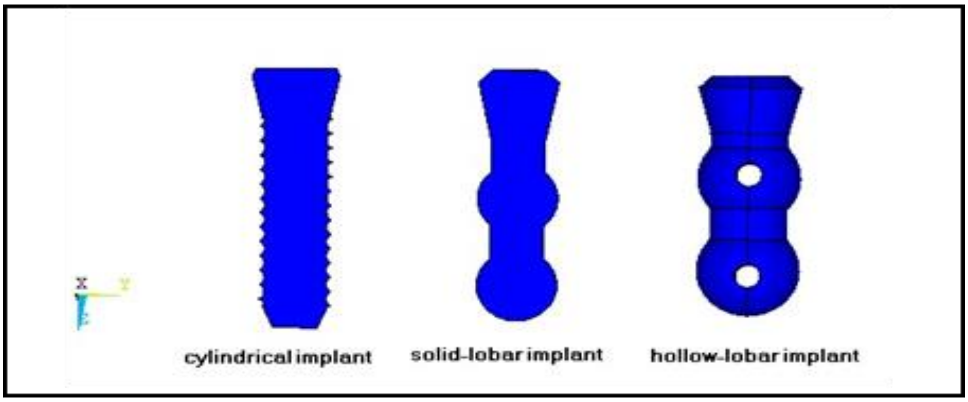

Figure 1:The geometry of models

Loading and Restraints

The use of a large number of elements is especially important for this problem because of the stress singularities expected at sharp corners. An axisymmetric FE model is constructed for all implant-abutment-bone systems.

Implants and abutments are modeled as Ti6Al4V with linear elastic, isotropic, and homogeneous properties. The Young's modulus of the titanium alloy is 110 GPa and Poisson's ratio is 0.35 [4]. All implant models are surrounded by a block of simulated homogeneous bone with linear elasticity.

Cortical bone is modeled as a 3 mm thick layer with an elastic modulus of 14 GPa and Poisson's ratio of 0.3, surrounded by a 17 mm thick layer of trabecular bone with an elastic modulus of 1.37 GPa and Poisson's ratio of 0.31. The geometrical and mass properties of the three implants are listed in Table .1.

Table.1: Models characteristics and mass properties

Characteristics	Cylindrical Implant	Solid-Lobar Implant	Hollow-lobar implant
Diameter	4mm	4mm	4mm
Length	14mm	14mm	14mm
Density	0.0044 g/mm3	0.0044 g/mm3	0.0044 g/mm3
No. of elements	7605	6686	6830
No. of nodes	1757	1518	30023

The forces exerted on an abutment vary in direction and magnitude. On a single tooth or implant, the largest forces occur along the axial direction. The axial loads have been measured to vary between 77 and 2440 N [5]. Generally, the lateral component of the occlusal force is significantly smaller and considered to be less than 100 N [6]. In this work, three types of loads were applied to the abutment to simulate different loading conditions that can be seen during mastication or biting in implants that carry single tooth. These are vertical (0 < FV < 2500 N) and lateral (0 < FL < 500 N) loads applied on the vertical axis of the implant, and bending moments (0 < M < 4000 N.mm). By investigating the effects of the components, the details of the load transfer mechanisms of the different implants can be identified. Figure.2. gives a schematic depiction of the loads.Inferior border of the bone block was fixed in order not to occure any possible movements [7] & [8].

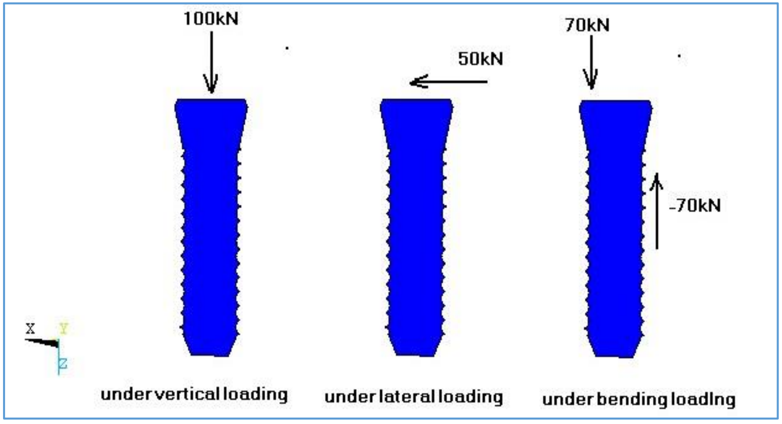

Figure 2:, the details of the load

The ANSYS Finite Element Package (version 5.7) was used to design and generate the three implant models described above (Figure 1.). The generated 3D model volumes were discretized using 8-node explicit brick elements. Free mesh and mapped meshing were used together to generate the model. The bone-implant interface was considered as a perfect union, indicating complete osteointegration. Care was taken to use a very fine FE mesh to represent the implant and bone model

. All materials used in the model were considered isotropic, homogeneous and linearly elastic. Young's modulus and Poisson's ratio of mandibular and implant materials are summarized in Table 2.

Table 2:*Mechanical properties of oral tissues and implant.*

Materials	Young’s modulus (GPa)	Poisson’s ratio
Titanium(implant)	110	0.35
Cortical bone	14	0.3
Cancellous bone	1.37	0.31

Results

The results of this are dedicated to study the effects of geometry parameters on stress distribution in the prostheses and bone. Representative stress data for the lower jaw bone of the dental implant subjected to a three forces are shown in Figures (3 to 5).

1. *Influence of geometrical parameters on stress distribution in implants*

In general, high stresses were recorded in the neck region for all models. However, as shown in Figure (3), the stress concentration was higher in the cylindrical model than in any other model, with the highest stresses localized at the neck edge and the first implant strand. This stress localization can lead to stress shielding and ultimately implant loss.

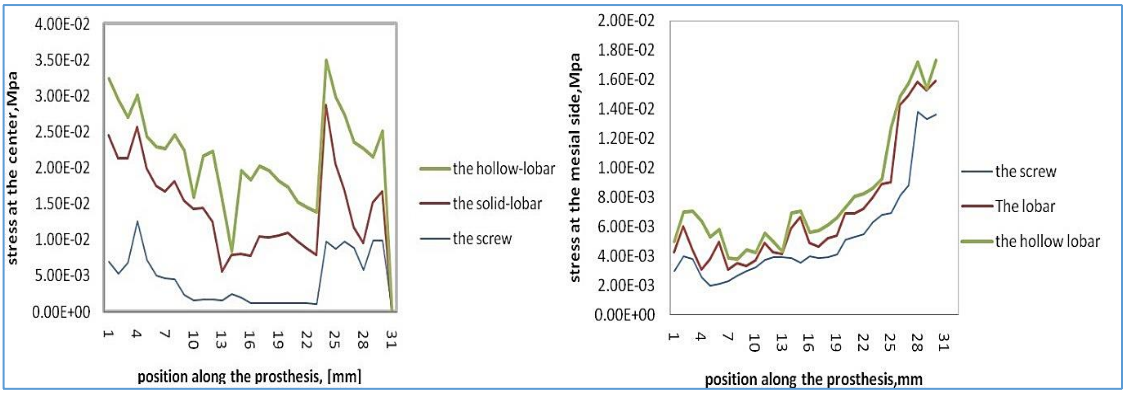

Figure 3:Stress distribution at the center and mesial side on the bone as a function of the implant designs.

In contrast, the hollow rover model showed better stress distribution than any other model under three different loading conditions, as can be seen in Figure (4). Specific comparisons between hollow and solid implants show that solid implants have less stress protection, although they both performed better than cylindrical implants.

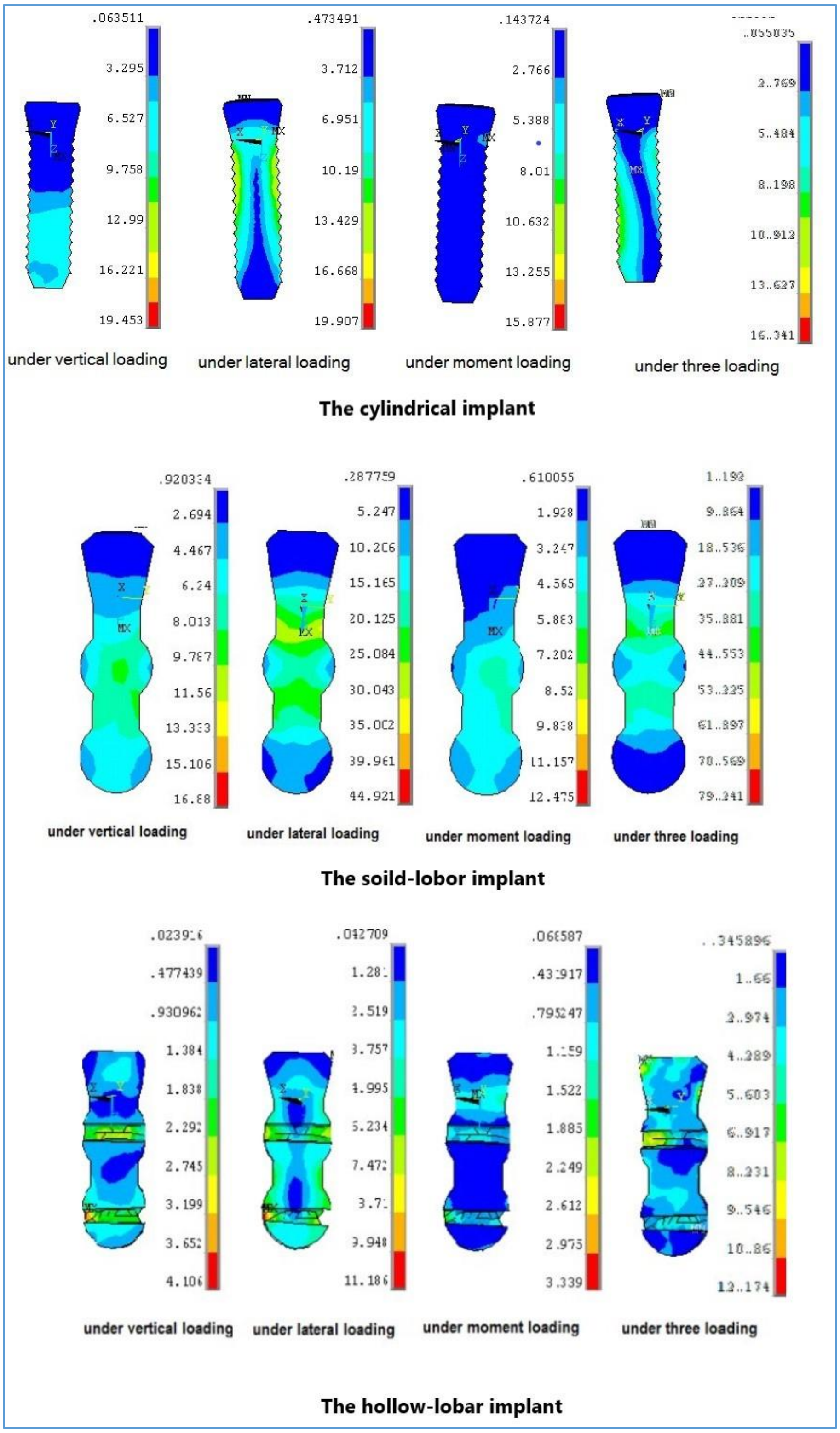

Figure 4: Shows von Mises stress distribution following the application of three different loading conditions in a fully osseointegrated bone-implant complex.

2. *Stress distribution in the mandible*

The generated model accounts for the different properties of cortical and trabecular bone from the overall distribution. The stress distribution in the mandible is shown in Figure (5-7). The high stresses recorded in all loading situations are concentrated in the cortical bone around the implant, while the stresses decrease in the trabecular bone region as a result of the very different stress ratio between cortical and trabecular bone. The highest von Mises stresses under vertical loading were observed at the base of the implant in all models, but their ratio was much lower than in the cortical bone. In contrast, the highest von Mises stresses under lateral loading occurred near the buccal and lingual cortical plates.

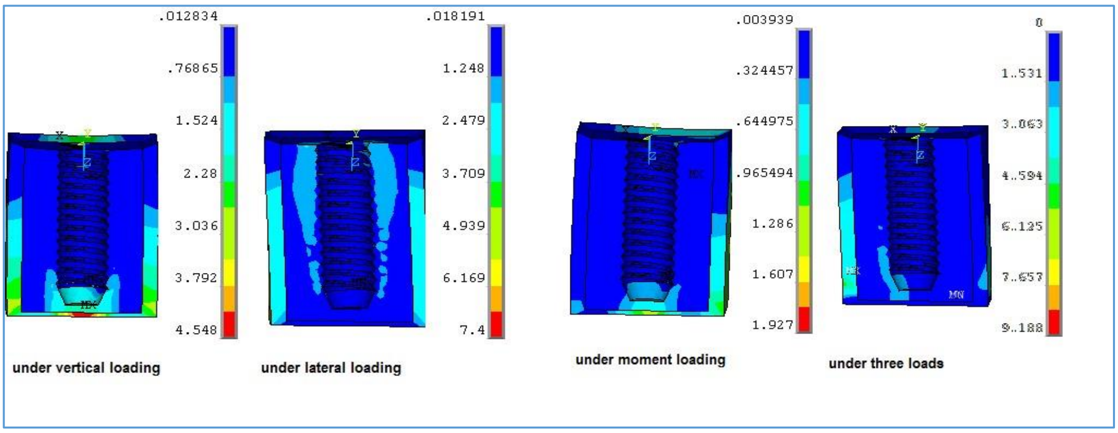

Figure 5:Stress distribution on the bone with the cylindrical implant.

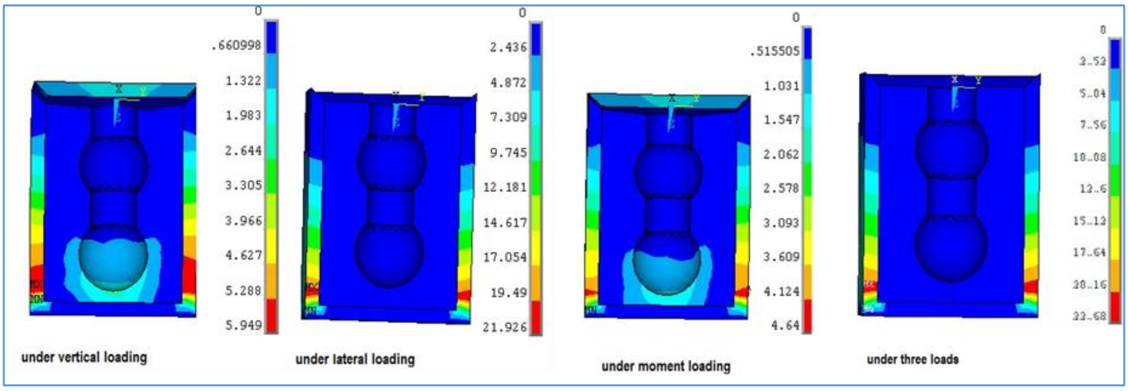

Figure 6:Stress distribution on the bone with the solid-lobar implant.

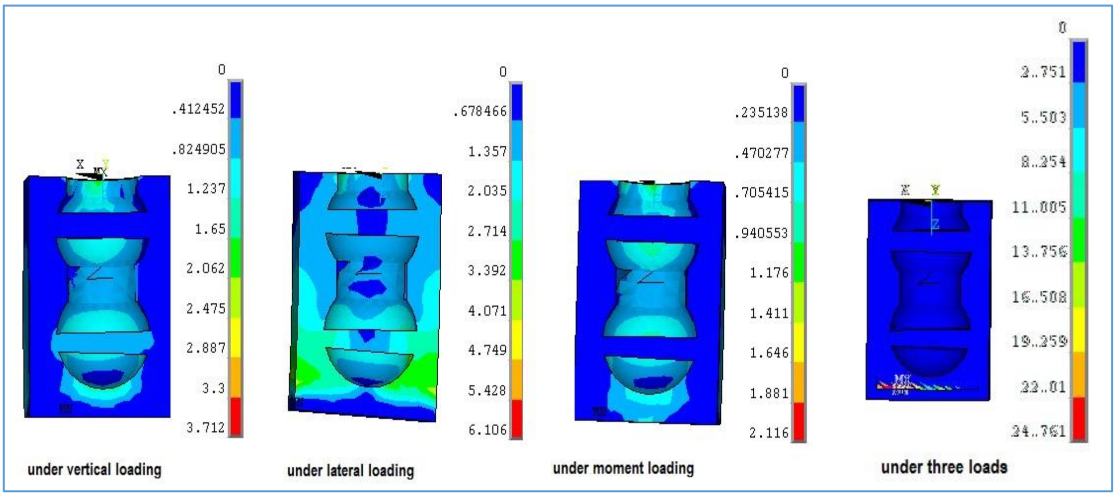

Figure 7:Stress distribution on the bone with the hollow-lobar implant.

3. *under vertical loading*

High stresses were localized circumferentially at the interface between cortical and trabecular bone and distributed horizontally across the cortical bone. The stresses were also applied to the cortical bone facing the resorption socket. The stresses were evenly distributed in the cortical and trabecular bone along the arc of the resorption depression. The intensity of stresses decreased significantly as bone resorption increased. In addition to the stresses in the cortical bone recesses, high stresses were also present in the cortical bone in close contact with the implant neck. On the other hand, a homogeneous stress distribution was observed in the bone in close contact with the implant neck, with lower stress intensity compared to models with cortical bone around the implant neck. The displacement was similar between the different models and was greater on the side of the bone-implant contact surface. The displacement clearly increased with progressive bone loss. Displacement in models with trabecular bone in contact with the implant neck was clearly greater than in models with cortical bone contact. The contact between cortical and cancellous bone was markedly flatter due to the different strain distribution in the models. Trabecular bone deformation gradually dissipated within the structure, whereas cortical bone deformation was limited to areas of reinforcement. No specific correlation was found between strain intensity and progressive marginal bone loss in both cortical and trabecular bone (Fig..8).

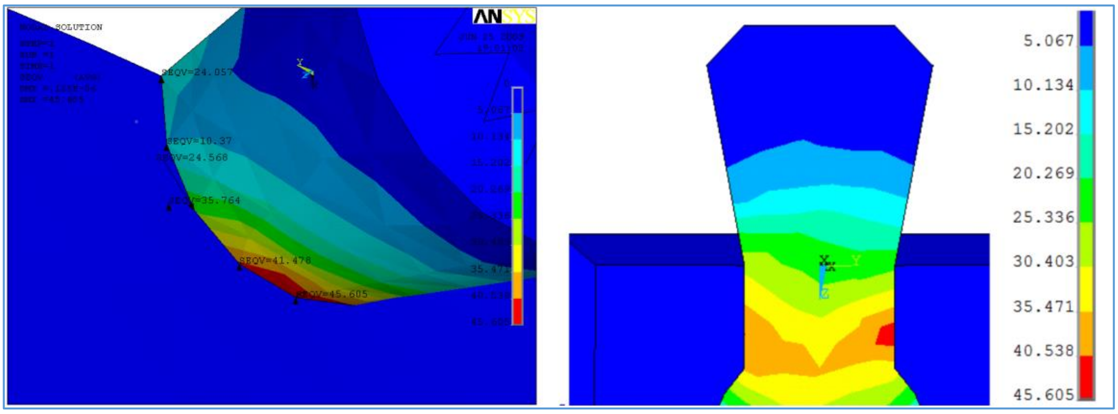

Figure 8: Simulation of progressive marginal bone loss around the implant.

4. *under lateral loading*

In the models, the stresses were concentrated on the side where the load was applied. Models with cortical bone in contact with the implant neck exhibited higher stresses than models with cancelled bone. Changes in stress intensity in cortical and trabecular bone did not correlate with progression of limbal bone loss (Fig..9). Peri-implant stress concentrations were found around the implant neck on the side opposite the loading side in the model. There was no clear correlation between stress intensity and progressive limbal bone loss in cortical and trabecular bone. The stress distribution in the cortical bone model was within the cortical bone as shown in Fig. (.9-A-). The model with cortical bone in contact with the implant neck showed less displacement than the model with cortical bone in contact with the implant neck as shown in Fig. (.9 -B-). The presence of cortical bone significantly reduced displacement, and even in the late stages of bone resorption, displacement was observed along the junction of cortical and trabecular bone rather than within the cortical bone, followed by distension dissipation in the trabecular bone.

Similarities were observed between the presented stress formation and displacement of bone tissue representatives. In all models, high stresses occurred around the implant neck. The intensity of the stresses did not increase as marginal bone loss progressed, unless cancellous bone was exposed in the implant neck region Fig. (.9 -B-).

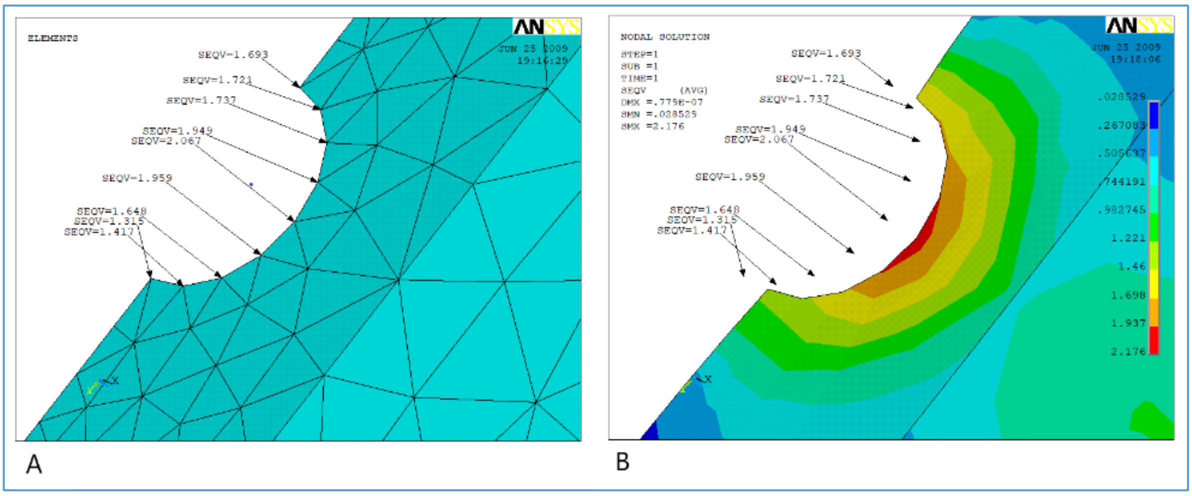

Figure 9: Under oblique loading, higher stresses were observed in models comprising cortical bone (a) than trabecular bone (b).

Discussion

Scientific efforts on the biomechanical evaluation of oral implants have included in vitro [21], in vivo animal and human studies [22, 23], ex vivo [24] human studies, and treatment-based clinical trials [25]. However, with the ever-increasing use of implants, it is still very difficult to determine the trade-off situations that make implant-supported prostheses biomechanically acceptable due to complications and physiological consequences. The assumptions adopted, such as modeling homogeneity, isotropy, and linear elasticity, may substantiate questions about the inadequacy of modeling biological systems. As with other experimental methods, claims based on accurate quantitative results from FE studies require validation, which is difficult to obtain due to the high variability in the mechanical properties of biological tissues. Nevertheless, however logical a hypothesis may be, it remains a hypothesis [26], and different information obtained under different experimental conditions may introduce uncertainty in the correct clinical interpretation and the approach to be taken [27]. In this regard, it should be noted that numerical simulations of biological tissue can only partially explain the biomechanical behavior of loading forces. Based on current knowledge, additional biological studies should provide answers to these questions.

Although there are currently many in vitro studies aimed at investigating the biomechanical state of peri-implant tissue as a function of loading in different scenarios, such approaches, especially for marginal bone defects, are still few due to the strong involvement of biological responses at the cellular level [28]. It has been suggested that some degree of tapered resorption is the result of biomechanical adaptation of bone to loads, and that as resorption progresses, the loads on the cancellous bone and implant under lateral loading may increase, leading to implant failure. Bra¨gger [29] observed on radiographs an increase in bone density, similar to that of the dura mater, during bone resorption in clinically stable implants. However, the radiographic appearance of normal teeth suggests that the dura is a thin layer of dense bone called the cribriform lamina; the name lamina dura (hard layer) is derived from the radiographic appearance and description of a thin layer of compact bone. This bone is no more highly mineralized than the trabecular body of the adjacent trabecular bone. To date, there have been no studies quantifying the mechanical properties of alveolar bone as marginal bone loss progresses, and there is no scientific evidence regarding cortical bone remodeling. Therefore, the assumption of cortical bone in models of bone defects of various shapes and sizes is highly questionable. Therefore, basic research is needed to determine the nature of bone that may appear after progressive bone loss. In the present study, the magnitude and distribution of stresses, strains, and displacements in cortical and trabecular bone were not similar under vertical and oblique loading. On the contrary, the values under vertical loading were significantly less than those under oblique loading. The intraosseous tilt of the implant, as indicated by the displacement values, was greater under oblique loading conditions, resulting in a tilt of the implant above the level of the cortical bone. This suggests that implant necks surrounded by trabecular bone exhibit approximately 10 times more intraosseous displacement under oblique loading compared to vertical loading. This result indicates that bone loss around the implant neck almost doubles the deformation gradient. Given that oblique loading also increases implant displacement, the biomechanical results can reach clinically significant levels, as an increased strain gradient can lead to unrecoverable bone or microfracture of the bone under load. Depending on the outcome of this worst case scenario, progressive bone loss can also be expected to lead to implant failure.

The causes of fracture are complex and can be related to various factors including high stress concentration, oral fluid, different masticatory patterns and loads. Considering the above factors and referring to the modeling results, it can be show that the two most important design parameters, implant stresses and masticatory muscle stresses, should be considered before selecting a material for an implant-supported fixed prosthesis.

Stresses on the retained implant. Based on this analysis, reveal models with high values of implant stresses and adding a new design parameter (one-piece implants) to the selection process, i.e., models with low retained implant stresses, the results of finite element analysis show that stress protection in dental implant prosthetics can be minimized. The results of finite element analysis show a good trade-off between stress protection and mechanical performance of dental implant prostheses.

Conclusion

This finite element analysis highlights the critical interplay between implant geometry and peri-implant bone integrity in determining stress distribution around anterior dental implants. Threaded cylindrical implants exhibited the highest stress concentrations, particularly under conditions of marginal bone loss, suggesting increased biomechanical risk. In contrast, hollow rover implants demonstrated more balanced stress profiles, especially in trabecular bone, though potentially at the expense of mechanical resistance.

Marginal bone loss significantly amplifies stress in cortical regions, underscoring the importance of preserving crestal bone for long-term implant success. The results suggest that implant selection should be tailored not only to anatomical constraints but also to the biomechanical environment, with one-piece or hollow designs offering potential advantages in compromised bone scenarios.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.