RESEARCH

Comparing static, dynamic and impact loading behavior of biomimetic porous dental implants with conventional dental implants (3d finite element analysis)

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ABSTRACT

Comparing static, dynamic and impact loading behavior of biomimetic porous dental implants with conventional dental implants (3d finite element analysis)

Background: Porous structures instead of bulk structures have been suggested for implants because porous structures have elactic modulus similar to natural bone and allow bone tissue ingrowth. But there are limited studies to simulate porous implants with different amount of porosity at different locations The purpose of this study was to evaluate the stress distribution levels at cortical and spongious bone tissue that occurred around commercially available dental implants and four different biomimetic implant design with various porous parts and porosity amounts.

Methods: 3-dimensional finite element analysis was conducted using mathematical models of unilateral 3-unit cantilever fixed partial dentures (FPD) subjected to vertical and oblique rotated static, dynamic and impact occlusal loads. Vertical load of 300 N was applied to the model over the central fossa of the crowns. Oblique load of 50 N were applied per tooth over the functional palatinal tubercule at an angle of 45 °.

Results: Impact loading conditions create excessive stress values at distal dense titanium implants (1030 MPa). This was more than the ultimate tensile strength of dense titanium alloy Ti-6Al-4V (930 MPa). It might be summarized as fully porous and middle section porous implants showed lower stress values at distal implant for all loading conditions.

Conclusion: The location of porosity is more critical than the amount of porosity for stress distribution. The distributions of stress at implants and surrounding bone mainly depended on the location of the porosity. Impact loading is a critical parameter for implant-supported prosthesis. Observance and prevention of impact loading should be considered for designing biomimetic porous implants. The porous biomimetic implant design with porous middle sections was the most successful design to decrease impact loading stress.

KEYWORDS

Porous biomimetic implant, impact loading, finite element analysis

ÖZ

Biyomimetik poröz dental implantların konvansiyonel dental implantlarla statik, dinamik ve çarpma yükleme koşullarında davranışlarının karşılaştırılması (3 boyutlu sonlu eleman analizi)

Amaç: Kemiğe benzer elastik modül değerleri ve kemik dokusunun gelişimin izin vermesi sebebi ile biomimetik poröz yapılar, konvansiyonel implantların yerine önerilmiştir. Ancak, farklı porözite oranına ve porözitenin farklı bölgelerde bulunmasını simüle edecek sınırlı çalışma vardır. Bu çalışmanın amacı, konvansiyonel dental implantlar ile çeşitli bölgelerinde poröziteye sahip ve farklı miktarlarda porozite içeren dört farklı biyomimetik implant tasarımı etrafındaki kortikal ve spongioz kemik dokusunda meydana gelen stres dağılım düzeylerini değerlendirmektir.

Gereç ve Yöntemler: 3 boyutlu sonlu eleman analizi için, üstçene posterior bölgede 2 adet implant üzerine yapılan 3 üyeli kanat uzantılı sabit bölümlü protez matematiksel olarak modellendi. Elde edilen model üzerine, dikey ve oblik uygulanmış; statik, dinamik ve çarpma yükleri uygulanmıştır. Vertikal yük olarak kronların merkezi fossaları üzerinde 300 N dikey yük uygulanmıştır. Oblik yüklemede her bir dişin fonksiyonel palatinal tüberkülüne 45 ° 'lik bir açı ile 50 N yük uygulanmıştır.

Bulgular: Çarpma yüklerinde, distaldeki konvansiyonel implant üzerinde aşırı stres değerleri oluşmuştur (1030 MPa). Bu değer titanyum alaşımının (Ti-6Al-4V) nihai gerilme mukavemetinden (930 MPa) daha fazladır. Sonuçlar, tüm yüzeyi gözenekli ve orta üçlü bölümü gözenekli implantların tüm yükleme koşulları için distal implantta daha düşük stres değerleri gösterdiği şeklinde özetlenebilir.

Sonuç: Stres dağılımı açısından; porözitenin yeri, porözite miktarından daha kritiktir. Çarpma yükleme, implant destekli protez için kritik bir parametredir. Biyomimetik poröz implantların tasarımı için çarpma yükünün gözlenmesi ve önlenmesi düşünülmelidir. Orta üçlüsü poröz biyomimetik implant tasarımı, çarpma yükleme stresini azaltmak için en başarılı tasarımdır.

ANAHTAR KELİMELER

Biyomimetik poröz implant, çarpma yükleme, sonlu eleman analizi

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Titanium is a common material in dental and orthopedic implants because of its biocompatibility, high corrosion resistance, and durable structure. This allows direct healthy contact between bone and implant surface.[1,2]

There is an elastic modulus inconsistency between dense bulk titanium and the human bone. Bulk implant structures cause stress between the implant and bone, which can lead to problems such as bone atrophy.[3-5] Reducing the elastic modulus of bulk titanium can avoid mismatch between the elastic modulus of human bone and titanium material.[6,7] The use of porous scaffold structures instead of bulk structures have been suggested because these porous structures are similar to natural bone and allow bone tissue ingrowth, proliferation of cells, vascularization and mineralization in the porous spaces. The growth of bone into porous areas maintains the long-term mechanical fixation into the host skeleton. In addition, the porous titanium has bone-like mechanical properties that could resist loading conditions imposed on human bone.[4,8]

Porous structures with increased porosity and pore size are clearly preferred for new bone growth because they have elastic modulus values similar to surrounding bone by Karageorgiou et al.[9] but increased porosity and pore size can also weaken the mechanical properties.[10,11]

There are limited in vivo studies, in one of the studies, porous orthopedic implants with 40–50% ratios of porous structure showed both optimal ingrowth areas of the bone and adequate mechanical resistance.[12]

Finite element analysis (FEA) is an analytical tool to measure stresses and deformations. It offers detailed quantitative data on any object and is frequently used in dental stress analysis.[13] FEA is also widely used to predict the biomechanical performance of different implant designs and environmental factors on implant success.

Although many investigations have reported the mechanical performance of dental implant designs, most of these studies analyzed the biomechanical performance with static loading effects. To simulate real load activity, the dynamic and impact loads should not be ignored. In this study, dynamic and impact loading conditions were analyzed in addition to static loading conditions.[14,15]

The aim of this study was to evaluate the stress distribution levels at cortical and spongious bone tissue that occurred around commercially available dental implants and experimental implants of varying porosity (fully porous, middle section porous, apical and middle section porous and only apically porous) under extreme load levels. To evaluate the stress distributions within the bone around the dental implants, 3-dimensional finite element analysis was conducted using implants, 3-dimensional finite element analysis was conducted using mathematical models of implants.

MATERIALS AND METHODS

This study compared a commercially available dental implant (4 mm x 11 mm Astra; Astra Tech AB, Mölndal, Sweden) and four different biomimetic implant design with various porous parts. The first implant model (DI) was bulk (fully dense) with a high elastic modulus (Fig. 1A). The second model (FPI) included a dense core and fully porous outer layer (Fig. 1B). The third model (MPI) had porous structures in the middle section (Fig. 1C). The fourth model (AMPI) was porous at the apical and middle sections (Fig. 1D). Only the apical side was porous structured in the fifth implant model (API) (Fig. 1E). The porous parts of the biomimetic porous implant designs contain two porous layers with different features. The first layer was on the outer side and has 70% porosity. The second layer was on the inner side and was 30% porous. All porous implant designs include a dense core to ensure clinical requirements.

The research was carried out by static lineer analysis with three dimensional finite element stress analysis method. Intel Xeon ® R CPU 3, 30 GHz processor, 500 gb Hard disk, 14 GB RAM and Windows 7 Ultimate Version Service Pack operating system, 3D scanner with optical scanner Activity 880 (smart optics Sensortechnik GmbH, Sinterstrasse 8, D-44795 Bochum, Germany), VRMesh Studio (VirtualGrid Inc, Bellevue City, WA, USA) and Algor Fempro (ALGOR, Inc. 150 Beta Drive Pittsburgh, PA 15238-2932, USA) from 3-D modeling software Rhinoceros 4.0 (3670 Woodland Park Ave N, Seattle, WA 98103 USA) USA) analysis program were used for structuring 3-D network homogenization, 3-D solid model creation and finite element stress analysis.

For modeling bone tissue, an adult patient's maxilla was scanned with Conical Beam Tomography (ILUMA, Orthocad, CBCT, 3M Imtec, Oklahoma, USA). Data taken from Conical Beam Tomography were transfered into 3d-doctor software and the bone texture was separated by Hounsfield Values by "Interactive Segmentation" method. After the decomposition process, 3D model was obtained by "3d Complex Render" method and the bone texture was modeled.

Processing finite element models

A graphic processing program (Abaques) was used to construct the mathematical models. The models consist of bone, implant parts (implant, abutment, abutment screw) and fixed partial dentures (FPD). The diameters and heights of the implants were selected to be comparable in size: 4.0 mm in diameter and 11 mm in length. The implants were inserted 3 mm apart from each other. The elastic modulus of dense titanium was selected for conventional implant with a dense core of biomimetic implants, abutments and abutment screws. The FPDs were modeled as maxillar first premolar and maxillar second premolar; the first molar was a cantilevered superstructure over the implants. Porcelain fused metal (PFM) was modeled as a superstructure material. The elastic modulus of cobalt-chronium alloy for framework and feldsphatic porcelain for occlusal veneer material were set for FPD model (Figure 1). The thickness values of the porcelain and the metal sets were 1.5 mm and 0.5 mm. The cement layer between the crown and abutment was too thin to adequately model in the finite element simulation and was considered negligible for modeling purposes.

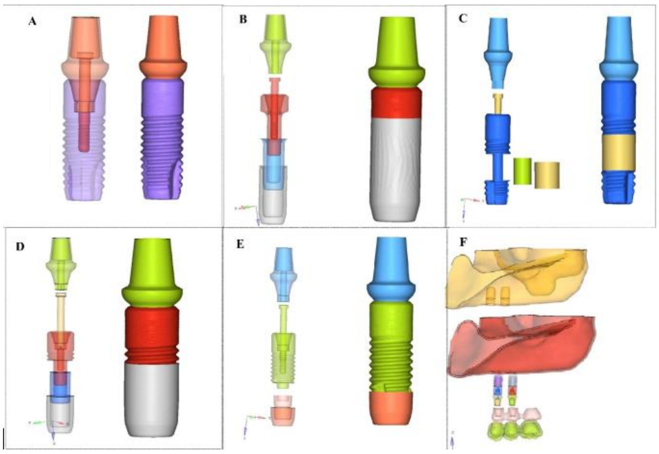

Figure 1

Dental implant models A) Fully dense conventional implant (DI). B) Biomimetic porous implant with dense core and fully porous outer layer (FPI). C) Porous biomimetic implant with porous middle section (MPI). D) Apical and middle section porous biomimetic implant (AMPI). E) Apically porous biomimetic implant (API). F) The model consist of bone, implant parts (implant, abutment, abutment screw) and fixed partial denture (FPD).

Material properties

All materials were isotropic, homogenous, and linearly elastic. For bone, this enabled the creation of complex models. The elastic properties used in the model were taken from the literature as shown in Table 1. All interfaces between the materials were assumed to be bonded or osseointegrated. Materials were accepted to be isothropic, homogenous and linearly elastic.

Table 1.

Mechanical properties of materials

	Modulus of elasticity GPa	Poisson's ratio	Ref No
Co-Cr alloy	218	0.33	39
Feldspathic Porcelain	82.2	0.35	39
Cortical bone	13,7	0.30	39, 47
Spongious bone	1.37	0.30	39, 47
%70 porous titanium alloy	11	0.33	12, 47, 57
% 30 porous titanium alloy	19	0.33	12, 47
Ti-6Al-4V	110	0.35	39

Loading conditions

Implants generally worked at static loading conditions in the literature, but it is essential to analyze dynamic and impact loading conditions to ensure the behavior of implant design. The applied forces were vertical and oblique rotated static, dynamic and impact occlusal loads. Stress levels were calculated using von Mises stress values.

Occlusal forces were applied on occlusal contact regions as described by Okeson.[16] A general occlusal force was selected based on previous reports.[17-20] A static, vertical load of 300 N was applied to the model. The loads were applied simultaneously over the central fossa of the crowns. Static, oblique load of 50 N were applied per tooth over the functional palatinal tubercule at an angle of 45 ° to the occlusal plane.

The vertical and oblique dynamic loading conditions were applied to same regions with the same occlusal loads. A time-dependent 10 s masticatory load is applied for dynamic load. A force with a peak of 800 N, a rise time of 2 ms, and a total duration of 4 ms was chosen for impact loading.[21,22]

RESULTS

Stress distribution at the implants under static, dynamic and impact loading conditions

The maximum von Mises stresses at conventional and biomimetic mesial and distal implants are shown in Figure 2.

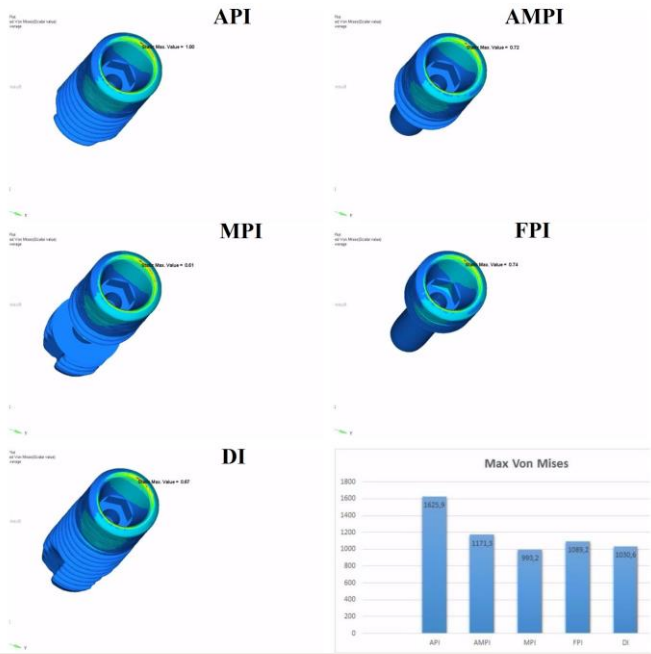

Figure 2

Maximum Von Mises stresses on distal implant at impact oblique loading conditions.

The lowest stress values were observed on the MPI biomimetic implants when the mesial implant was loaded vertically, although the highest stress values occur in the DI for both static and dynamic impact vertical loading conditions. API created the highest stress levels in static oblique loading conditions for both implants. At dynamic oblique and impact oblique loading conditions, the highest stress levels were observed in AMPI and in API. Although lower stress levels were observed for dynamic and impact oblique loading conditions in MPI implants, the DI showed lower stress values at static oblique loading conditions.

Higher stress values were indicated in API and AMPI biomimetic implants at oblique loading conditions. The highest von Mises stress value was detected for API distal implant at an oblique impact loading condition (1625.9 N). The oblique impact-loaded API mesial implant also showed high stress levels (1293.6 N).

Lower von Mises stress values were observed for mesial MPI biomimetic implant for all loading conditions except static oblique loading conditions. The MPI porous distal implant created lower stresses at dynamic oblique and impact oblique loading conditions.

FPI biomimetic implant created lower stress values at static vertical, dynamic vertical and impact vertical loading conditions.

Generally, it might be summarized as MPI and FPI implants showed lower stress values at distal implant for all loading conditions (Figure 3).

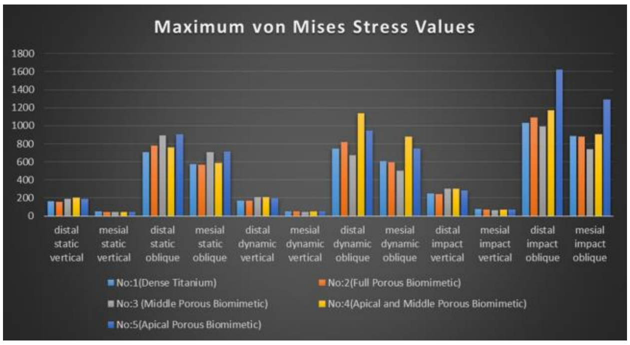

Figure 3

Maximum von Mises stresses on mesial and distal implants at static, dynamic and impact loading conditions.

Stress distribution at cortical bone under static, dynamic and impact loading conditions

The highest stress levels were observed around FPI biomimetic implants and the lower stress levels were observed around DI under all static loading conditions for both implants (Figure 4, Figure 5).

The highest stress value was detected for cortical bone in the API distal implant at impact oblique loading condition (203.6 N). Also, the cortical bone around the impact oblique loaded FPI mesial implant showed the highest stress level (155,2 N). Lower stress values were observed for cortical bone around vertical static loaded AMPI mesial implant (Figure 5). Generally the lowest stress values were observed at cortical bone around MPI implants for both implants under impact and dynamic loading conditions.

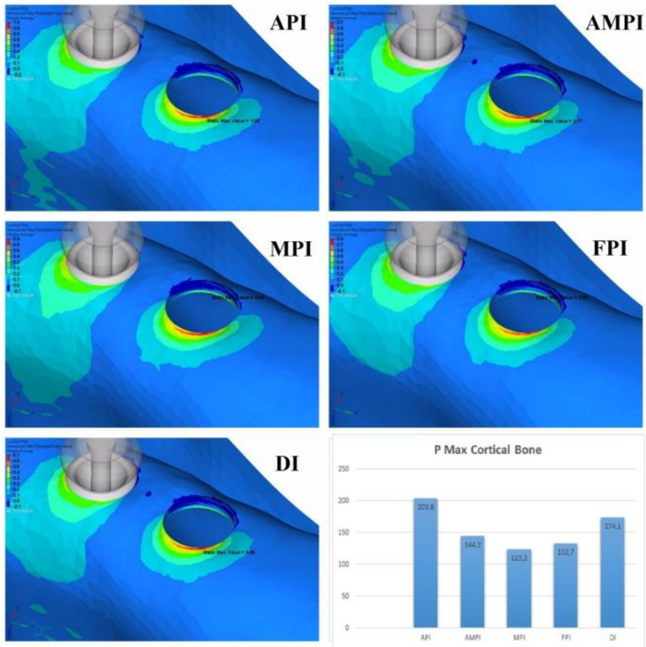

Figure 4

Maximum stresses on cortical bone around distal implant at impact oblique loading conditions.

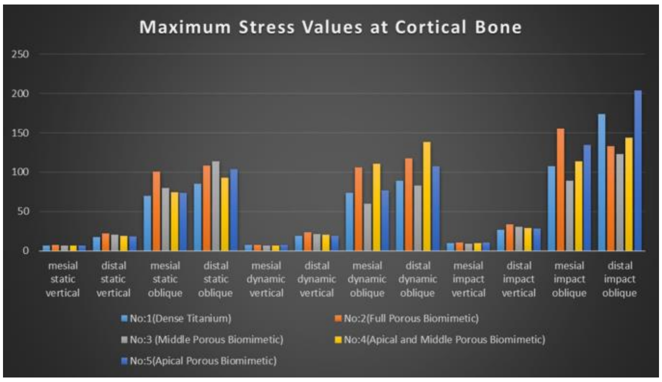

Figure 5

Stress distrubitions of cortical bone around mesial and distal implants at static, dynamic and impact loading conditions.

Stress distribution at cancellous bone under static, dynamic and impact loading conditions

The highest stress concentrations in cancellous bone occurred around DI implants at static, dynamic and impact vertical loading conditions (Figure 6, Figure 7). Although higher maximum stress values were seen in different implant types at oblique loading conditions, the

AMPI and API implants generally created higher stress concentrations in cancellous bone at all oblique loading types. The maximum stress occurred around the oblique impact loaded distal API implant (21.8 N). Minimum stress values were seen around the static loaded mesial FPI implant (1 N).

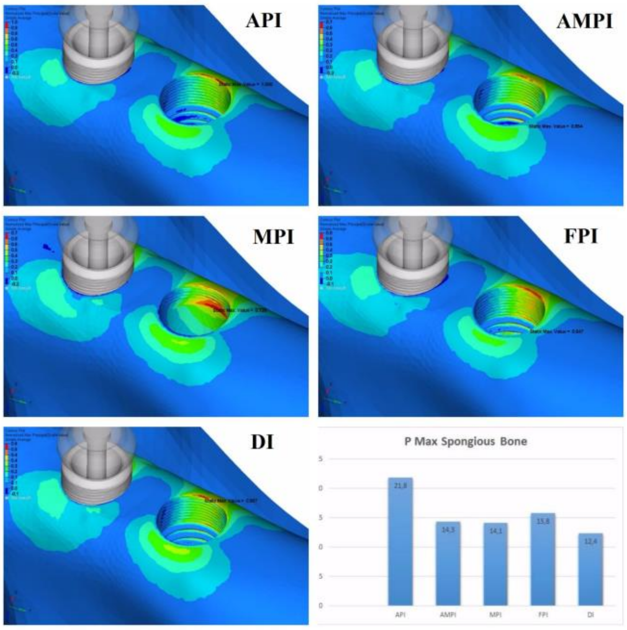

Figure 6

Maximum stresses on cancellous bone around distal implant at impact oblique loading conditions.

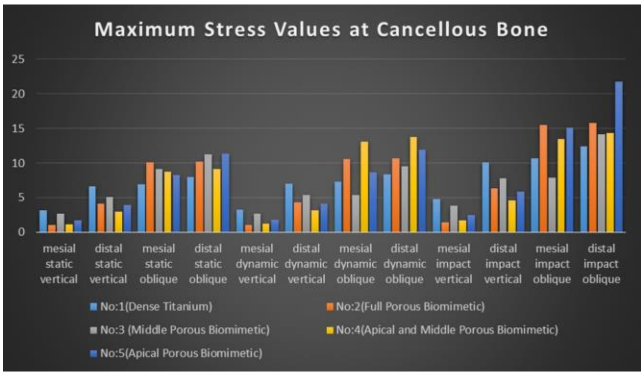

Figure 7

Stress distrubitions of cancellous bone around mesial and distal implants at static, dynamic and impact loading conditions.

DISCUSSION

Fixation by osseointegration determines the bone/implant interface, and the mechanical environment impacts the success of the implant. Numerous implant designs and surface modifications have been made to ensure superior osseointegration.[23]

Two principles are critical in implant design. First, the load should be reduced to avoid overloading. Second, the contact area between the bone and the implant should be increased.[24-26] Increasing the surface roughness improves attachment and proliferation of bone-forming cells. The surface roughness affects the initial osseointegration, and using porous structures can maintain suitable surfaces for ingrowth of bone structures.[27-30] Adapting mechanical properties to the surrounding bone tissue can prevent bone loss.[31,32] Porosity of the scaffolds can be basically grouped into two types. The first is a foam-like structure with irregular pore dispersions, dissimilar pore geometry and closed pores .[33,34] The second has cage like structure with similar pore sizes, controlled pore dispersions and open pores. Additive manufacturing methods are used to fabricate open-pored scaffold structures.[35-37]

Different levels in pore sizes are called graded porosity and suggest a multifunctional porous implant. Even if the porous structure is necessary for connection between the implant and the bone, a dense core is still necessary for load-bearing parts.[38] Larger porous structures must be used at the outer side of implant to provide optimal circumstances for bone ingrowth and reduce the Young's modulus. Furthermore, reducing the size of pores and the amount of the porosity towards the core of the implant provides dense structure-resistant occlusal loads.[39] In light of this information, a three-layered porous scaffold was designed for this study. The porous scaffold design consists of two porous layers 70% in the outer and 35% in the inner both covered a dense core to meet clinical requirements.

Different prosthetic designs can restore missing teeth. In some situations, it is not possible to use two abutment teeth at each end of the edentulous area to support FPDs. In such a clinical situation, a FPD can be designed with a distal cantilever to replace the missing teeth. Anatomical limitations such as the maxillary sinus or mental foramen/inferior alveolar nerve would preclude the insertion of implants. Unfavorable local conditions of the residual edentulous ridges may lead to the treatment of a partially edentulous site with a cantilever-fixed prosthesis. Edentulous ridges next to implants can be reconstructed via cantilevers, and this is a simple and economical procedure.[40-42] Excessive stress was induced in surrounding bone at fixed partial dentures with cantilever.[17,43] Thus, a cantilever bridge was chosen to monitor the behavior of the new biomimetic implant designs at extreme loading conditions.

The maximum bite force changes with individuals and regions in the dental arch.[44] Evidence-based studies indicate that the average bite force is 100-150 N for adult humans.[45] There is no significant difference between the biting force in patients with implant-supported fixed partial dentures and patients with natural teeth.[46,47] Therefore a general occlusal force was selected considering these values. A load of 150 N was applied to the models. However, it is not necessary for this force to match reality exactly because of the standardization between conditions seen in this study; the conditions were qualitatively compared to each other.

Although static load analyses are generally used in the implant literature, dynamic and impact loading conditions must be considered to evaluate the optimal implant design.[48] To reflect the exact clinical situations, dynamic and impact loading conditions were essential for finite element analysis. Although dynamic loading conditions add more stress to the implant and the surrounding bone, the location of the maximum stress level at static and dynamic stress values differ from each other.[15,49] The maximum closure speed of the mandible is estimated to be between 85 and 140 mm/s.[50,51] We selected 150 N for every crown with 0.02 seconds for impact loading.

This study is the first to analyze the effect of the location of porosity on the behavior of porous structured dental implants under extreme loading conditions. We cannot generalize across different implant types, but the location of the porosity influences stress distribution. The AMPI and API implants create more von Mises stresses on the mesial and distal implants under all loading conditions. When the maximum stress levels in the cortical bone were evaluated, the lowest stress concentrations were observed around the DI implants at static loading and around the MPI implants under dynamic and impact loading. MPI implants reduce the stress between the bone-implant interface in the cortical bone zone, which is important for the long-term success of the implants. The higher porosity on the outer layer can match the elastic modulus of the surrounding bone.[48]

Impact force resistance is one of the main features of rigid implants. Implants may be exposed to dynamic and impact shock stress during the mastication process during the lifecycle. The impact tests explain the weakest point of the samples and define the material damage by deformation.[52] After analyzing the test results, we can conclude that API implants are not suitable in terms of impact resistance. When maximum stress values were 887.5 N for DI mesial implant under oblique impact loading, the stress values dramatically rise to 905.1 N for AMPI and 1293.6 N for API biomimetic implants. In contrast, the stress levels decreased for MPI biomimetic mesial (737.8 N) and distal implants (993.2 N).

The bone crest around the implant fixture may act as lever fulcrum point when a flexural force is applied so the crestal area of an implant should be dense so as to bear the load. The results showed that if the apical region was porous then the stresses would be higher than the others in every loading conditions. According to the results of this study, it can be emphasized that the middle section porous biomimetic implant design was ideal for the long-term stability of implant. This type of design is beneficial for the transfer of internal stress from the implant to surrounding bone. These results were in accordance with the results of Chen et al.[51]

The results show that impact loading conditions create excessive stress values at distal dense titanium implants (1030 MPa). This was more than the ultimate tensile strength of dense titanium alloy Ti-6Al-4V (930 MPa).[53-55]

Although there are limited data about the ultimate tensile strength of porous titanium alloys, the bend strength for 42% laser sintered porous titanium was 316.6 MPa versus and similar compressive strength values for cortical bone. Cantilever bridges and impact loading should be avoided.[56]

Porous biomimetic implants can be considered to be fully osseointegrated with excellent biological and mechanical properties and porous titanium is an outstanding biomaterial structure that can achieve a stable bone-implant interface and has excellent biological and mechanical properties. The amount of porous surfaces, the location of the porosity and the distribution and morphology of the porous areas are critical factors for analyzing the mechanical behavior of porous biomimetic dental implants.

CONCLUSIONS

Considering the limitations of this study, It was concluded as:

1. The location of porosity is more critical than the amount of porosity for stress distribution. The distributions of stress at implants, implant screws, cortical bone and cancellous bone mainly depended on the location of the porosity. The von Misses stresses at mesial and distal implants increased with apical location of porosity.
2. Impact loading is a critical parameter for implant-supported prosthesis. Observance and prevention of impact loading should be considered for designing biomimetic porous implants.
3. The porous biomimetic implant design with porous middle sections was the most successful design to decrease impact loading stress.
4. Recent innovations in biomedical technology made biomimetic porous implants significantly more accessible especially orthopedic clinical and research communities. More studies must be done into the biomimetic porous implants to promote alternative implant materials.

5. Finite element analyses were performed on idealized geometric models. The mechanical properties of biomimetic porous titanium alloys with different amounts of porosity were referred from publications that did not consider the bone ingrowth in porous scaffolds. Pore morphology and bone ingrowth have significant effects on the mechanical properties of the porous titanium alloy. Bone ingrowth is likely the most important factor. Bone filling increases the mechanical properties of the biomimetic porous implant including Young's modulus and yield stress. Thus, stress concentrations will be lower than reported values.

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COMPETING INTERESTS

The authors claim to have no financial interest, either directly, or indirectly, in the products or information listed in the article.

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