Biomechanical Investigation of Resilient Dental Implant Design by Finite Element Analysis

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Abstract: This study investigated the biomechanical behavior of implant design that forms an integral part of tooth-implant support prostheses. The research presents a 3D finite element analysis for three different models, one of which was designed with a shock absorber implant. To make the study more qualitative, implant design has been compared once with the classical tooth-implant support prostheses model and once again with the tooth-support support prostheses model. The prostheses model with the resilient implant of the cushioning element shows impressive results since they reduce the von Mises stresses and the over-mechanical loading around the natural tooth and implant under various loading conditions. Finally, it concluded that a resilient implant with a cushioning element design transfers stresses more efficiently than other implant designs, and successfully handles the biomechanical problems related to combining natural teeth with implants.

Keywords: dental implant, shock absorber, dental prostheses, resilient, finite element analysis.

الملخص: هذا البحث يتناول السلوك الميكانيكي الحيوي لتصميم الغرسات التي تُستخدم كجزء أساسي في تركيبات الأسنان المدعومة بالغرسات والأسنان الطبيعية. يقدم البحث تحليل العناصر المحدودة ثلاثي الأبعاد لثلاثة نماذج مختلفة، يتضمن أحدها تصميمًا جديدًا لغرسة ممتصة للصدمات. ولجعل الدراسة أكثر دقة، تم مقارنة تصميم الغرسات مع النموذج التقليدي لتركيبات الأسنان المدعومة بالغرسات والأسنان الطبيعية، وأيضاً مع النموذج المدعوم بالأسنان الطبيعية فقط.
أظهرت النتائج أن النموذج المزود بغرسة ذات عنصر ممتص للصدمات يحقق أداءً متميزًا، حيث يقلل من إجهادات فون ميسيس والإجهادات الميكانيكية الزائدة حول الأسنان الطبيعية والغرسات تحت ظروف تحميل متنوعة. وخلصت الدراسة إلى أن تصميم الغرسة المبتكر المزود بعنصر ممتص للصدمات ينقل الإجهادات بشكل أكثر كفاءة مقارنة بتصاميم الغرسات الأخرى، ويعالج المشاكل البيوميكانيكية المتعلقة بدمج الأسنان الطبيعية مع الغرسات.
الكلمات المفتاحية: زراعة الأسنان، ممتص الصدمات، تركيبات الأسنان، مرونة، تحليل العناصر المحدودة.

Introduction

Combining teeth into an implant to support a prosthesis has been shown to be an efficient modality of treatment because the implant is joined to residual natural teeth whenever there is an anatomic limitation or poor remaining bone, and implanting more than one implant is difficult [1].

Resiliency of dental implant component, cushioning effect of cement and/or rapper layer, and force deflection in superstructure [2], may play a significant rule to this kind of prosthesis. Therefore, there remains a question surrounding the biomechanical impact of the mismatch in movement between teeth and implants [3].

Some previous research tried to create designs of dental implants that have tooth-like mobility and stress absorbers only in an axial direction [4]. Although they had acceptable results, the periodontal ligament enables the tooth to move not only in the vertical direction but also in other directions as well [5]. Other researches recommend applying three-dimensional shock absorber to simulate the mechanical performance of the periodontal ligament, which allows the generated stresses to be passed to the bone in a more natural way [6].

This study aimed to investigate the biomechanical behavior of shock absorber design of dental implant that form the integral part of tooth-implant fixed prostheses.

Materials And Methods

A. The Design of the Implant System with Cushioning Element

This Resilient Implant was influenced by a new dental implant design presented by Avram Manea et al. [6]. It has a cushioning element between the fixture and the abutment, to provide the required movement for the implant system, Figure 1

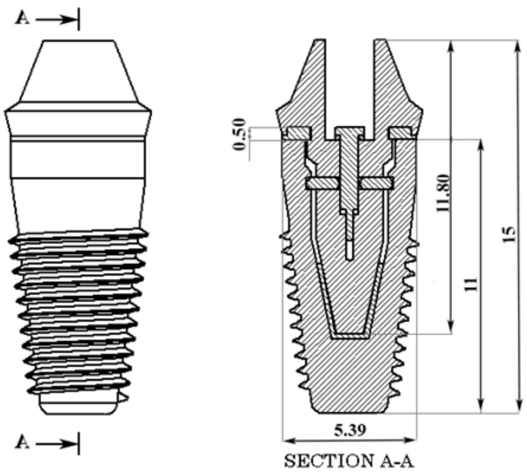

Figure 1: Side and sectional views and main dimensions of Resilient Implant Design with Cushioning Element.

The abutment was connected to the implant by a pin and a lock, so the abutment was not tightened rigidly to the implant, therefore the screw fractur, which is a common problem in most resilient implant designs, could be avoided.

This design contains two cushioning elements located between the fixture and the abutment to provide micro-flexibility and absorption to occlusion loads. The internal surface of the implant was lined with a cushioning element of 0.2 mm thickness, while the other cushioning element between the abutment and the implant platform was designed as an O-ring to increase the tightness

In general, bio-compatible materials have been developed for a variety of functions. Bio-compatible materials, such as silicon, poly-ether-ether-ketone (PEEK), and Polyoxymethylene (POM), have been chosen to work as a cushioning element in many resilient implant designs [7,8]. In the present design, the O-ring element, which is made of POM is positioned between the fixture platform and abutment, whereas the silicon was lined at the bottom of the internal cavity of the implant. To make sure the resilient element responds in the desired way, all the available resilient materials that were mentioned in previous studies have been tested during the design of the present undertaken implant.

B. Finite Element Analysis of the study models

The research presents finite element analysis for three different tooth - implant supported prosthesis models, one of which was designed with shock absorbers. To make the study more qualitative, implant design has been compared once with the classical tooth-implant fixed partial denture model and once again with the tooth-support fixed partial denture model. The simulated models included the first premolar, first molar, cortical bone, calculus bone, periodontal ligament, dental implant, and the Zirconia dental prosthesis with non-rigid connectors.

The three undertaken three-dimensional models were first designed using SolidWorks_17, computer aid design software, then they have been exported to ANSYS_16 Workbench software for further mechanical analysis.

The three models were manipulated as a tooth-supported dental prosthesis model (Figure 2), a tooth-implant supported dental prosthesis provided with different designs of dental implants, which are classical dental implant (Figure 3), and resilient implant of cushioning element (Figure 4).

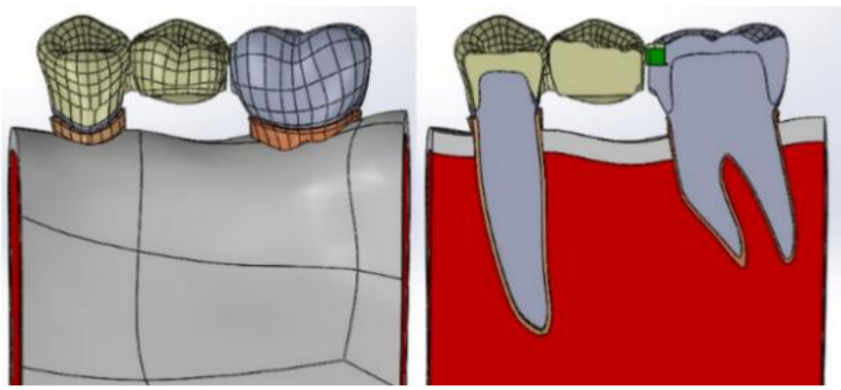

Figure 2: Tooth-supported dental prosthesis model.

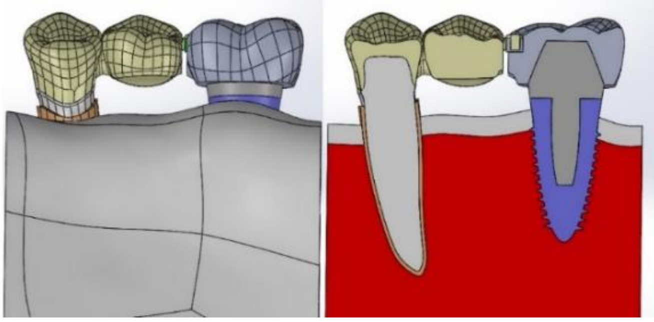

Figure 3: Model of dental prosthesis with classical implant design.

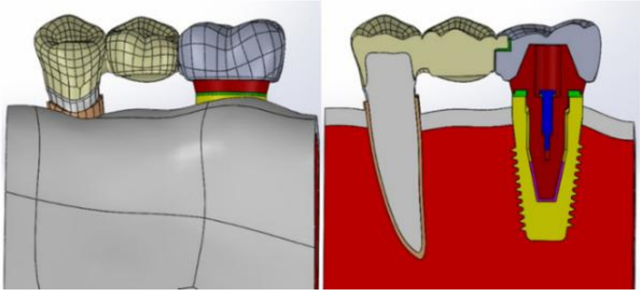

Figure 4: Model of dental prosthesis with resilient implant of cushioning element.

The periodontal ligament was generated from the root surface of premolar and molar geometries with a 0.2 mm thickness.
Some stress analysis studies showed that non-rigid connectors create more stress on the implant while also helping to reduce stress on the bone and reduce tooth intrusion [9]. There are various designs of non-rigid connectors available, but the most common is that one of key and keyway, the unite of stress backer [10]. In this unit the keyway is engraved in the implant crown while the key is prominent from the side of the pontic to be engaged with the keyway.
The models were meshing generation with element sizes of 0.5mm at a Global Level. Table 1.

Table 1: The total number of elements and nodes.

Models	Element	Nodes
tooth-supported prosthesis	405532	598108
Dental prosthesis with classical implant	99831	174605
Dental prosthesis provided with resilient implant of cushioning element	115193	201765

Biological tissues is an anisotropic and heterogeneous material which means that they have different mechanical properties for loading in different directions [11]. The material properties used for the current models were assumed to be isotropic, linear, and homogeneous, Table 2.

Table 2: Materials' mechanical properties.

Materials	Young's modulus (MPa)	Passion's ratio
Cortical bone [12,13]	15,000	0.3
Cancellous bone [12,13]	1,500	0.3
Periodontal ligament (PDL)[14]	69	0.45
Dentin [15]	18,600	0.31
Titanium [16]	110,000	0.35
Zirconia[14]	210,000	0.27
Polyoxymethylene (POM) [17]	3,450	0.35
Silicone [18]	6	0.49
Nonrigid connector [9]	110,000	0.42

This study has considered two different cases of force occlusion represented in two different simulations. In one simulation the applied force was considered vertical, while in the second simulation, the semi-values of these forces were re-applied to the occlusal surface from buccolingual directions with inclination of 30° to the vertical axis of the prosthesis [19].

The direction characterization of the applied forces was illustrated in on figure, Figure 5, in which along the z-axis the applied forces were as fellow; 450 N was applied on the top surface of the first premolar, 600 N was on the top surface of the second premolar, and 720 N was applied on the top surface of the first molar.

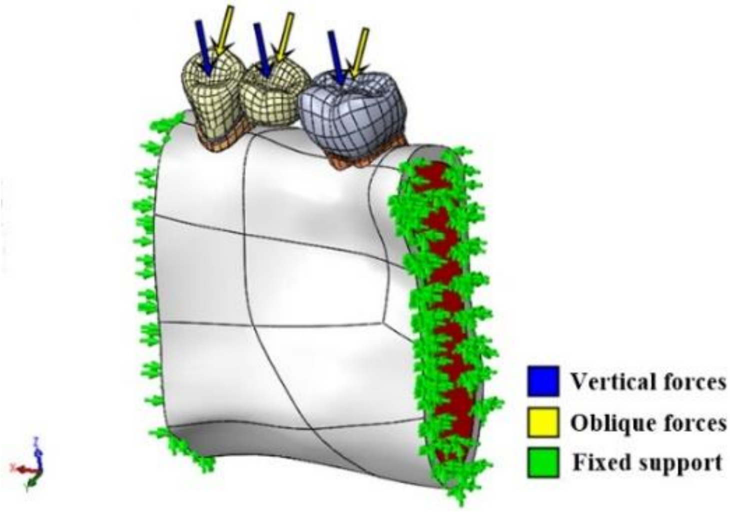

Figure 5: The applied forces.

The boundary conditions in most FEA simulations of the mandible are fixed [20]. The model is a sectional part of the alveolar so the bone model was supposed to be fixed in all directions.

Results

In the study, the von Mises evaluation was used to determine the stress distribution in the bone at the mesial and distal sides of the tooth and dental implant. Below are the analysis results:

A. ***Tooth-supported dental prosthesis model***

Under vertical loading, the maximum equivalent von Mises stress was about 3795 MPa in the prostheses, particularly in the nonrigid connector. The stress distribution in the bone around the roots was uniform, with similar values. in the mesial side of the neck area, the stress around the molar and premolar was 10.4 MPa and 10.9 MPa, respectively, while in the apex area, the stresses decreased. On the distal side, the stress generated in the bone around the molar and the premolar was 6.3 MPa and 6.7 MPa, respectively. However, the stresses increase gradually all the way down to the tip of the root area (Figure 6).

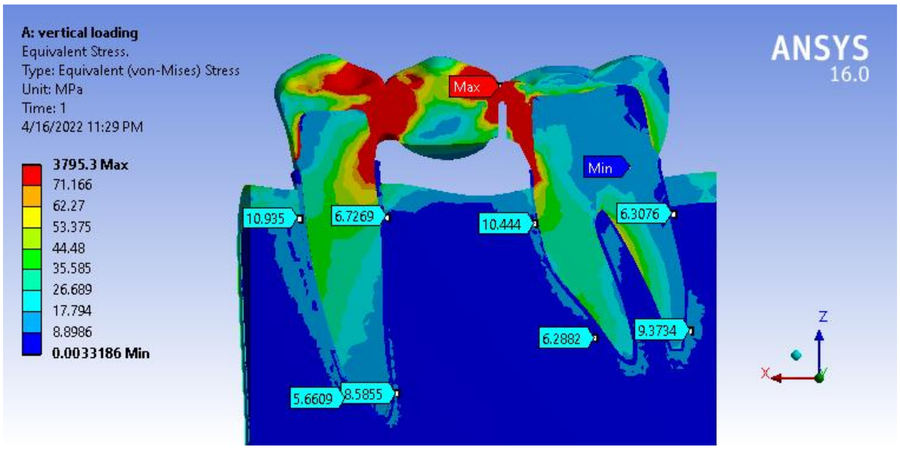

Figure 6: The von Mises stress under vertical load applied on Tooth supported dental prosthesis model.

Under oblique loading, the von Mises stresses elevated to the maximum value up to 3846 MPa at nonrigid connector. The stresses around the molar tooth were 9 MPa on the mesial side and almost 7 MPa on the distal side, whereas in the premolar tooth they were higher of about 13.2 MPa in the mesial and 8.3 MPa in the distal, as shown in Figure 7.

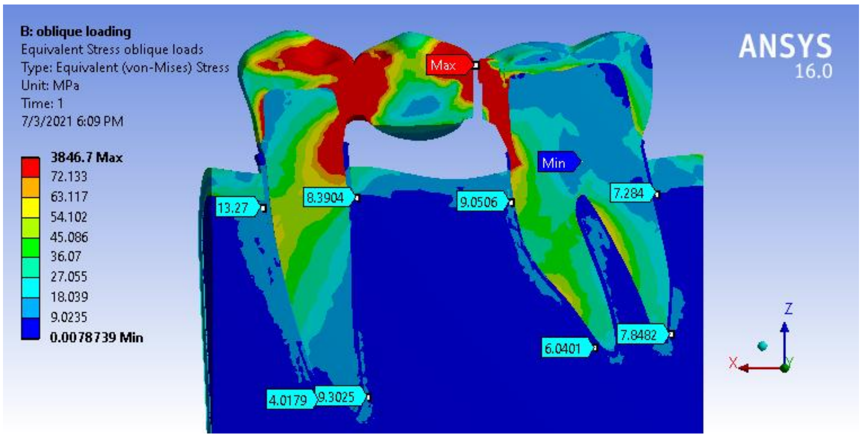

Figure 7: The von Mises stress under oblique load applied on Tooth supported dental prosthesis model.

B. ***Tooth-implant supported dental prosthesis with classical implant design.***

Under vertical loading, the maximum stress, 2442 MPa, generated in the model was located in the non-rigid connector. The stress distribution around the support units was clearly irregular, with different values that were influenced by bending moment due to the mobility mismatch between the teeth and Osseo integrated implants. The recorded stresses near the dental implant were 6 MPa on the mesial and 10 MPa on the distal side, while those generated around the natural tooth were 10 MPa on the mesial side and 5 MPa on the distal side, Figure 8.

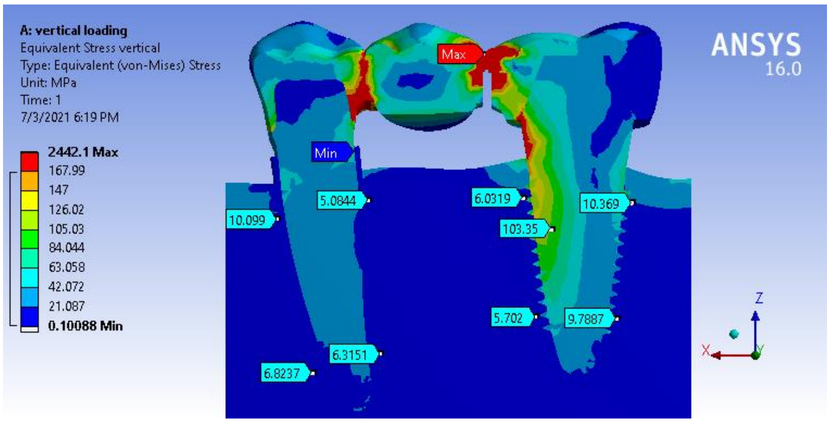

Figure 8: The von Mises stress under vertical load applied on model of dental prosthesis with classical implant.

Under oblique loading, the maximum stress increased to 3656 MPa. The area around the implant region showed higher stress than the area around the premolar root. Under this loading, a high amount of stress concentration was noted at the premolar root tip. As a result of these stresses, tooth intrusion may occur. However, there wasn't sensible effects of the oblique loading in the bone close to the implant comparing to that of vertical one, since it was 6 MPa on the mesial and 11.3 MPa distally. On the other hand, in the premolar area, the von Mises stresses were 10.6 MPa on the mesial and 5.2 MPa on the distal side, Figure 9.

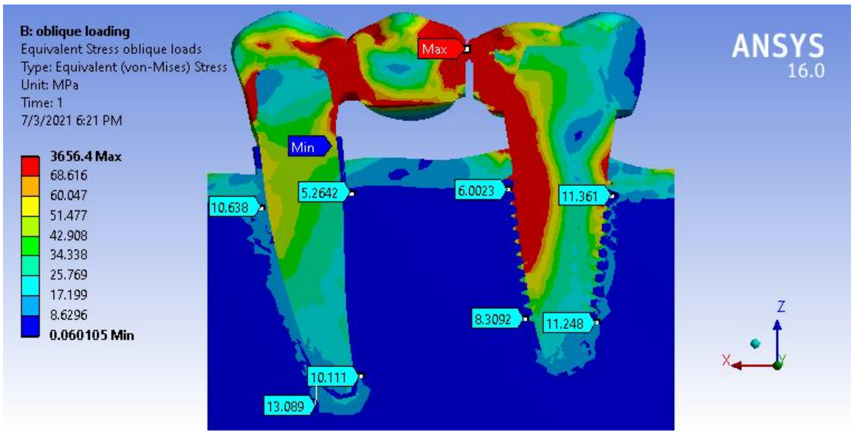

Figure 9: The von Mises stress under oblique load applied on model of dental prosthesis with classical implant.

C. Tooth-implant supported dental prosthesis provided with resilient implant of cushioning element.

Under vertical loading, this model shows the lowest value of maximum von Mises stress among all other undertaken models. The stresses were nearly identical around the implant area, since they record 4.5 MPa on the mesial side and 4.1 MPa on the distal side. The stresses around the premolar approach to normal levels were 10.5 MPa on the mesial side and 5.6 MPa on the distal side, Figure 10.

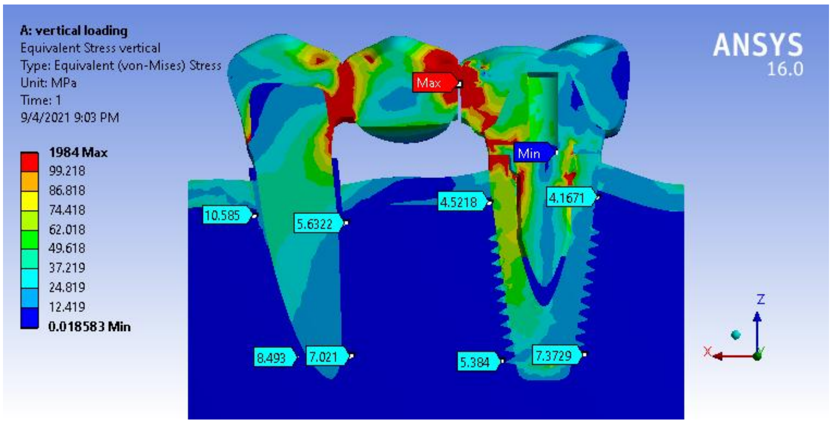

Figure 10: The von Mises stress under vertical loads applied on dental prosthesis with resilient implant of cushioning element.

However, under oblique loading the maximum von Mises stress increased to be 2109 MPa in the non-rigid connector. The stress around the implant reaches 5.3 MPa on the mesial side and 5.6 MPa on the distal side. While around the premolar the stress record rising on the mesial side to be 11 MPa and 6.3 MPa on the distal side, Figure 11.

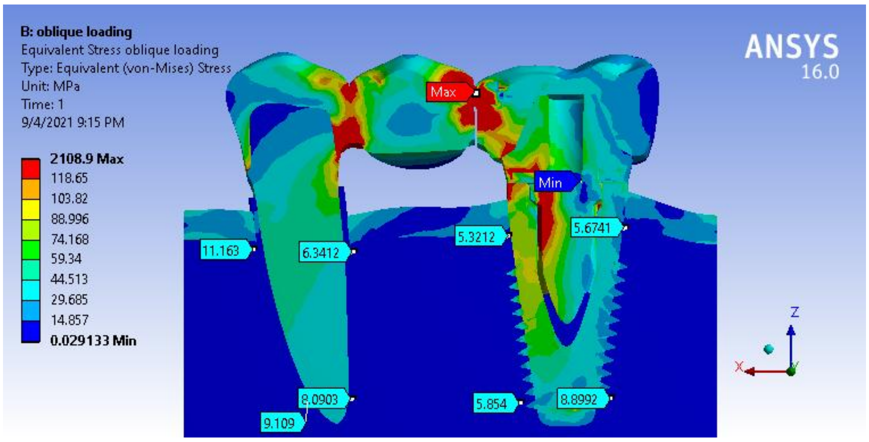

Figure 11: The von Mises stress under oblique loads applied on dental prosthesis with resilient implant of cushioning element.

Discussion

In mechanical systems, soft materials are commonly employed as dampers to reduce force transfer across inflexible components[18]. In the same way, a viscoelastic periodontal ligament subsisting between tooth and bone serves to dampen the masticatory stresses [21,22]. Similarly, in a resilient dental implant, an elastic shock absorber element inserted between the implant components can reduce the forces transferred to the surrounding bone [5,23]. Many researchers studied the use of teeth and implants to support dental bridges, but the effects are still controversial. Besides the advantages, there are potential consequences due to the biomechanical difference, such as tooth intrusion and bone loss [1,24]. According to dental literature, applying a non-rigid connector in a tooth-implant prosthesis can reduce bone resorption. At the same time, the rate of teeth intrusion may increase [10,13]

The effect of a resilient dental implant as a splint on the natural abutment has been discussed in several studies [3,6]. Most reported that using this kind of implant with resilient components has reduced the stress levels in the bone surrounding the tooth and implant [4,5].

In the present study, designs of resilient implants with shock absorber mechanisms was compared with a natural tooth to evaluate the ability of implant to mimic the movement of PDL based on the stress criteria by using finite element approach. The generated stresses in the bone around the support units was compared with an implant with rigid components. The implants were combined with a tooth in a dental prosthesis by a non-rigid connector. Vertical and oblique loads were applied to the occlusal surface of the prosthesis with the highest values of biting force to evaluate the mechanical behavior of the implant under extreme conditions.

In tooth-supported dental prosthesis model, the stresses in the bone around the teeth were almost the same under the vertical loads. The stress on the mesial side was higher and decreased all the way down to the apex of the root, whereas on the distal side the stresses were higher in the root apex area than in the neck area since the root apex was inclined distally, and the root's rotation center is located in the apical third [25]. Under oblique loads, the stress distribution pattern was similar to that under the vertical loading, in spite that its values were higher especially around the premolars.

The stress distribution pattern under vertical loads in the tooth-implant supported dental prosthesis model was disordered compared to that of the tooth-supported dental prosthesis model because of the mismatch in support unit mobility and differences in the centers of rotation of the implant and natural teeth. Furthermore, under oblique loads, high stresses were induced at the area of root apex, also the stresses around the implant neck were increased, which may result in tooth intrusion, bone loss, and eventually damage to the osseointegration. In addition, the cantilever effect played major role in creating bending moments owing to physiological tooth movement which in return could lead to prosthesis fracture, and implant failure.

In tooth-implant supported dental prosthesis with resilient implant of cushioning element model, the results were impressive since they showed a reduction in the von Mises stresses. When the stress result was compared to the tooth-supported dental prosthesis model, it revealed similar stress values around the premolar. However, the stress around the implant was less than around the natural tooth, which raises some concerns. On the other hand, the distribution of the stress patterns was more uniform than in a tooth-implant-supported dental prosthesis with a classical implant model. Also, the stresses in the premolar's root apical area were lower, which limited tooth intrusion. That means the resilient implant with cushioning element design reduces the over mechanical loading around the support units under vertical and oblique forces. Mehran Ashrafi et al [26]made a comparative study of implant designs with and without absorbers to analyzing the stress distributions in the implant and the bone, in addition to implant's relative micromovement, also showed the progression of destruction. The results showed that absorbers could reduce stresses in the bone surrounding the implant and thus bone loss could be minimized. In contrary, adding more absorbers element does not reduce the damage.

The ability of resilient dental implants to reduce the overloading in tooth-implant prosthesis was recorded in study by Omer Pektasx and Ergin Tonuk [5] in their analysis designed a resilient implant tries to imitate the tooth's mechanical behavior only in the axial movement, the results of the proposed implant approximated those of a natural tooth and lowered or effectively removed the reported troubles with ordinary implant. Also, when an elastic implant and a natural tooth were applied as a support for the bridge, the stresses at the bridge and abutment were reduced better than when a rigid implant was used. In the same context and from my point of view, since the geometries of both the bridge and the natural tooth were not professional, and the applied loads were just in a vertical direction the results were inaccurate, but one could consider this effort as a good base for resilient-implant design.

In general, the results obtained via the finite element method confirm the ability of the resilient implants to overcome the biomechanical complications related to combining natural teeth with implants, since these designs avoid tooth intrusion, manage stress concentration around the implant, reduce the cantilever effect, and limit bone loss. However, these designs need more improvement and investigation.

Conclusion

Finally, the following conclusion has been reached based on the present study results and observations:

- The classical implant design creates an uneven stress distribution pattern in bone, which causes tooth intrusion, bone loss, and damage to the osseointegration.
- The resilient implant with a cushioning element design transfers stresses more efficiently than other implant designs and successfully handles the biomechanical problems related to combining natural teeth with implants.

Conflict of Interests

No conflict of interest.

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