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THE BIOMECHANICAL EFFECT OF SUPRASTRUCTURE LOADING AND MATERIALS ON STRESS STATE OF IMPLANT SUPPORTED SINGLE RESTORATIONS 3D FINITE ELEMENT ANALYSIS

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ABSTRACT:

Objective: The aim of this numerical analysis was to evaluate the stress distribution and load transfer to the bone, via metal-ceramic, and all-ceramic single implant-supported prostheses (upper premolar crown) under functional forces.

Materials & Methods: A 3D Finite Element model was specially prepared to evaluate the performance of three-crown materials (In-Ceram alumina, zirconium, and Porcelain fused to metal), fixed with Glass ionomer cement type. In addition, Zinc phosphate cement was also tested with Porcelain fused to metal as a traditional type.

Results: Linear static stress analysis was performed to simulate 300 N loading on upper premolar distributed at Palatal Cusp Tip & Central Fossa with two different values in vertical and oblique directions.

Conclusions: Spongy bone and implant/abutment complex are insensitive to cement type with using Porcelain fused to metal crowns. Zirconium, and Porcelain fused to metal crowns behavior, is nearly the same, and much better than In-Ceram alumina ones.

Keywords: implant suprastructure material, Finite Element Method, cement-retained implant, cement-type

INTRODUCTION:

The use of osseointegrated dental implants for restoring the missing teeth, has currently become a commonly recognized and experienced treatment modality. The difficulties related to implant placement, endurance are constantly decreasing, and the success rate is increasing. Implant success depends not only on successful osseointegration, but also on the harmonious integration of a crown into the dental arch. Occlusal loading of osseointegrated implants is thought to be a decisive factor in the long-term success of an implant treatment course [1, 2].

The distributions and types of the applied stresses depend on directions of the applied loads and the formation of the implant superstructure restorative materials [3]. Selection of the type of material used on occlusal surfaces of implant-supported restorations is important because there can be destructive forces at the alveolar bone

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and implant interface exceed the bone's physiological strength threshold, the interface will likely fail. [1]. Because The connection between osseointegrated implants and the surrounding bone is direct and relatively stiff; therefore, it may be expected that an impact load applied to the implants will be transported to the bone directly, causing bone microdamage and then marginal bone loss [4].

In this regard, however, the in vitro and in vivo experimental results of a number of workers would appear to be somewhat controversial, flexible occlusal materials such as acrylic resin [5] have been advocated, especially in patients with inadequate marginal cortical bone, to reduce the impact effects arising from masticatory forces. However Ismail et al. [6] analyzed the effect of the occlusal materials (porcelain, precious, and non-precious alloy, acrylic or composite resin) on the stress in bone and implant, and they reported similar results for all the investigated materials. Also, in models of single implant-supported prostheses [7] and implant implant-supported complete arch prostheses [8], occlusal material did not influence bone stress; but in the model of the implant-supported complete arch prosthesis, it did influence retaining screw stress [9].

Different results obtained from the analysis of Skalak [2], a theory appeared that the loading of an implant made of a rigid occlusal material such as porcelain or metal may result in high impulse loading of the implant and the supporting bone. He has suggested that resins absorb shock, and thus reduce stresses on the implants and their supporting osseous structure [8-11].

However, the results of an *in vivo* study by Bassit et al.[12] showed that the resilience of an acrylic resin veneer is insufficient to cause significant change in the force transmission through the prosthesis as compared to a ceramic veneer. In addition, acrylic resins do not offer a sufficient abrasion resistance in order to allow a stable occlusal relationship [13]. Also, Eskitascıoglu et al. [14] investigated the influence of porcelain- and acrylic-based material on stress distribution when dynamic forces were applied in vertical and lateral directions on the design of metal-supported crowns over implants. Porcelains were found to absorb and distribute the stress in itself and consequently cause less transfer of stress to implant and surrounding tissue compared to acrylic-based materials.

Base metal alloys have exceptional physical properties. For example, they exhibit the highest modulus of any alloy type used for cast restorations [15] and have better castability than noble-metal alloys [16], but they tend to form thicker and darker oxide layers that may present esthetic problems [15].

Due to growing interest in esthetics and concerns about toxic and allergic reactions to certain alloys, patients and dentists have been looking for metal-free tooth-colored restorations. Therefore, the development of high strength dental ceramics, which appear to be less brittle, have less tensile strength, and are less subject to time dependent stress failure, has dominated the latter part of the twentieth century [17-19].

Because of their particular mechanical properties, all ceramic restorations exhibit a lower fracture resistance than ceramic restorations supported by metal substructures. To avoid these shortcomings, 2 types of industrially manufactured high-strength all-ceramic abutments with improved optical and mechanical properties are made available for implants: a densely sintered high-purity alumina (Al_2O_3) ceramic, and a Y_2O_3-partially- stabilized ZrO_2-ceramic implant abutment. However, the ZrO_2 abutments are more than twice as resistant to fracture as the Al_2O_3-abutments [20].

Zirconia is broadly used to construct prosthetic devices because of its good chemical properties, dimensional stability, high mechanical strength, toughness, and a Young's modulus (210 GPa) similar to that of stainless steel alloy (193 GPa). The mechanical properties of zirconia are the highest ever reported for any dental ceramic. The high initial strength and fracture toughness of zirconia results from a physical property of partially stabilized zirconia known as transformation toughening .On the other hand, its ability to transmit light and its white color, similar to the color of natural teeth, makes it useful in esthetic restorations of the oral cavity [21, 22].

Biomechanical considerations are recognized as being among the most important factors for the long-term success of the osseointegrated implant, Among the methods for the evaluation of implant biomechanics, three-dimensional (3D) finite-element analysis has been widely used for the quantitative evaluation of such stresses and strains in the bone due to technical limitations of stress assessment in bone in vivo [23,24].

The purpose of this study is to test the hypothesis that different superstructure materials may affect stress distribution and load transmission on porcelain, framework, implant, and supporting bone under functional forces. In addition, to determine the optimal material combination for the superstructure of an implant supported single restorations.

MATERIALS AND METHODS:

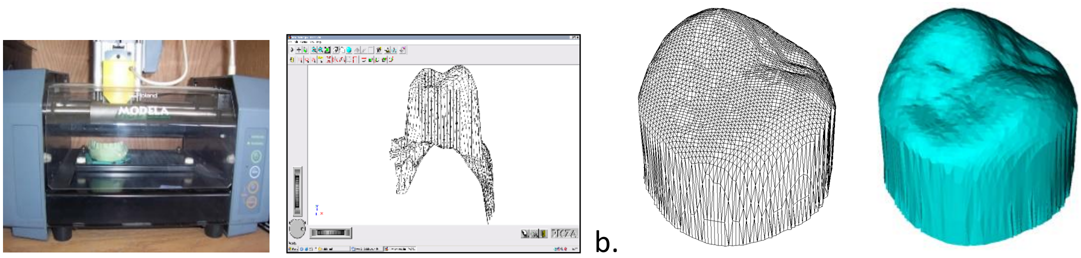
To investigate the effect of crown material and/or cement type on stress distribution in upper premolar restored, a 3D finite element model was developed. Bone geometry was simplified and simulated as two co-axial cylinders. The inner one represents the spongy bone (diameter 14 mm & height 22 mm) that filling the internal space of the outer cylinder (shell of 1mm thickness) that represents cortical bone (diameter 16 mm & height 24 mm) [25,26]. The implant-abutment complex (*Zimmer* *dental Inc, USA*) was drawn in three dimensions by commercial general-purpose CAD/CAM software “AutoDesk Inventor” version 8.0 (*Autodesk Inc., San Rafael, CA, USA*). The root form dental implant had nominal diameter of 3.7 mm, length of 13 mm and the shape of internal hex with hex width of 2.5 mm. The abutment was prepared for resting cement layer of 40 µm.

On the other hand the “Premolar crown” has too complicated geometry, therefore a three dimensional scanner was utilized for its modeling, Roland Modela - MDX-15 (Roland DG Corporation of Hamamatsu, Japan), to produce cloud of points or triangulations to be trimmed before using in any other application (see Figure 1).

Roland Active Piezoelectric Sensor and computer graphics program (Dr. PICZA) were utilized in acquiring and producing a data file contains a large set of points’ coordinates, usually called cloud of points. An intermediate, software was required (Rhinoceros vr. 3.0 - McNeel North America, Seattle, WA, USA) to find out a set of equally spaced planes intersecting the scattered points (Represent the scanned crown surface). Then each plane was divided into two parts, outer part (not required), and inner part represented the crown interior material. Finally, by the connection of these intersecting planes the crown geometry has been formed. The crown geometry was exported to finite element program as SAT file format [27].

On the finite element software environment ANSYS version 9 (ANSYS Inc., Canonsburg, PA, USA) set of operations like subtracting volumes to form cavities fits other parts to be assembled together in full contact. The final step was to ensure correct placement of the volumes and to secure error of overlapped materials during further analysis. All model parts were meshed (as presented in Figure 2), by 8 nodes brick element Solid 45 [28] which has three translation degrees of freedom in the global axes directions. Meshing process resulted in huge number of nodes, and elements, which are listed in Table 1. Crown material properties represent porcelain fused to metal (PFM), was calculated as weighted average of porcelain (55%), and NiCr (45%). While Table 2 lists the properties of the used materials. Figure 1 shows the crown geometry modeling to obtain careful three-dimensional manipulation of clinical variables.

a.



b.

Figure 1: a. 3D Scanner & screen shot of scanned crown, and b. final crown model

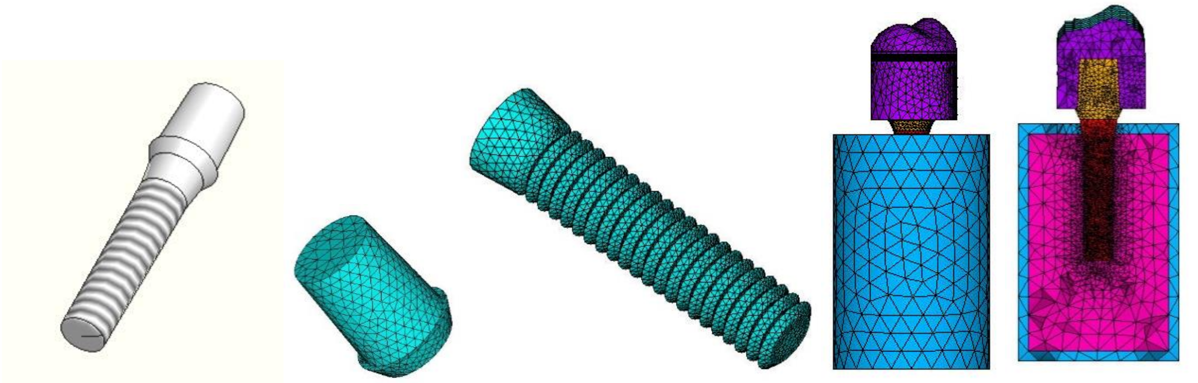


Figure 2: 3D F.E. meshed model components, and sectional view

The model was subjected to four different loading conditions by applying vertical and oblique loading as; two forces at Palatal Cusp Tip and Central Fossa each of 150N, and two forces at Palatal Cusp Tip and Central Fossa as 200 and 100 N respectively. The base of hollow cylinder representing the cortical bone was set to be fixed as a boundary condition. Linear static analysis was performed on a personal computer Intel Pentium Core 2 Duo, processor 3.0 GHz, 4.0 GB RAM.

Table 1: Number of nodes and elements in all parts of the model

Model Part	***Number of Nodes***	***Number of Elements***
Crown	***2,961***	***10,175***
Cement Layer	***867***	***2,524***
Implant	***9,643***	***46,751***
Abutment	***1,699***	***7,970***
Jaw Bone 1: Cortical	***1,156***	***3,515***
Jaw Bone 2: Spongy	***9,613***	***45,811***

Table 2: list the properties of the used materials

Model Part	***Material***	***Young's Modulus MPa***	***Poisson's Ratio (u)***
Crown	MCR: Porcelain / Ni-Cr	***149,450***	***0.34***
	In-ceram **Aluminum oxide glass ceramic core**	***418,000***	***0.22***
	Zirconia	***210,000***	***0.34***
Cement type 1	Glass Ionomer (medicem)	***12,000***	***0.35***
Cement type 2	Zinc phosphate	***22,400***	***0.25***
Implant	Titanium	***110,000***	***0.35***
Abutment	Titanium	***110,000***	***0.35***
Jaw Bone 1	Spongy	***1,370***	***0.30***
Jaw Bone 2	Cortical	***13,700***	***0.30***

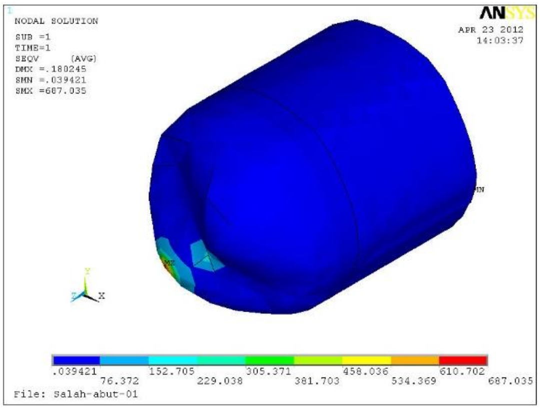
RESULTS:

Figures 3 to 7, represent samples of the obtained results with different crown materials, and cement materials, subjected to the four loading conditions on each part of the F.E. model. Vertical loading of 300 N was distributed at Palatal Cusp Tip & Central Fossa with two different values (2 x 150 N, and 100, 200 N respectively), the three crown materials and cement types showed the following behavior;

- In-Ceram crown received the highest value of Von Mises stress (687 Mpa), that about 25% higher), while the difference between zirconium, and Porcelain fused to metal was negligible (about 580 MPa).
- Values of total Crown deformation and Von Mises stress were reduced by about 17, 24% respectively, by applying equally distributed vertical loading regardless the cement type.
- Equally distributed vertical loading reduce cement layer total deformation and Von Mises stress by about 17, and 15 % respectively, in comparison with unequal loading for all tested crown materials and cement types.
- Applying equally distributed vertical load reduce implant/abutment total deformation and Von Mises stress by about 9, 12% respectively, in comparison with unequal loading.
- Vertical equal loading on crown reduces cortical bone Von Mises stress (about 20.5 MPa) by about 14%, in comparison with unequal loading (about 23.8 MPa).
- Crown material and/or cement type are negligibly affect cortical/spongy bone total deformation and von Mises stress.
- For all crown materials, equally distributed vertical loading reduce spongy bone Von Mises stress (about 26.4 MPa) by about 13%, in comparison with unequal loading (about 30.3 MPa).
- Cement type is negligibly affect crown and implant/abutment total deformation and von Mises stress

On the other hand, Figure 6(a) compare between cortical and spongy bone subjected to two different vertical loading cases (equal and unequal distribution); while Figure 6(b) compared between different loading conditions on different cement types supporting PFM crown.

(a)



(b)

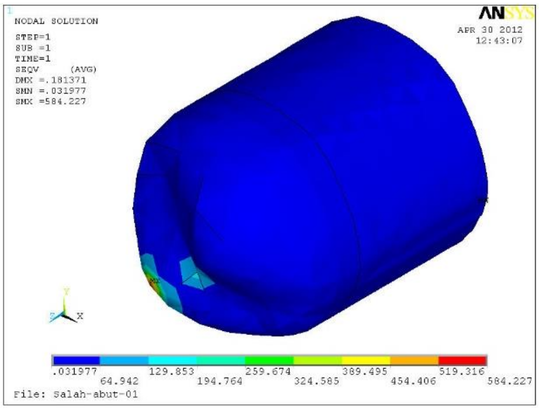
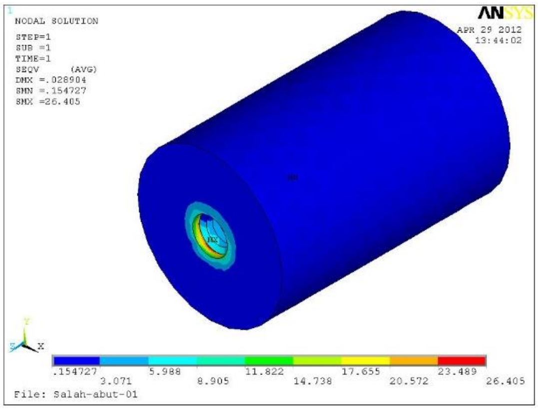


Figure 3: (a) In-Ceram and (b) zirconium crowns Von Mises stress distributions when loaded by 200N at Palatal Cusp Tip & 100N at Central Fossa. (R18, 42)

(a)



(b)

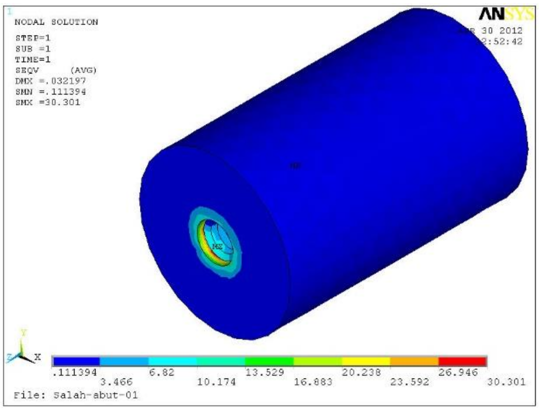
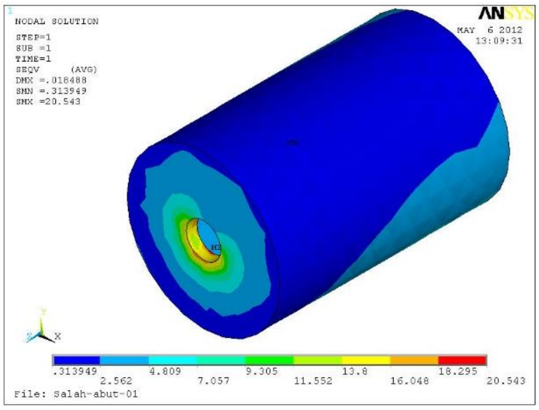


Figure 4: Von Mises stress of spongy bone under zirconium crown, and Glass ionomer cement layer with (a) equal and (b) non equal distributed vertical loading of 300N. (R41, 42)

(a)



(b)

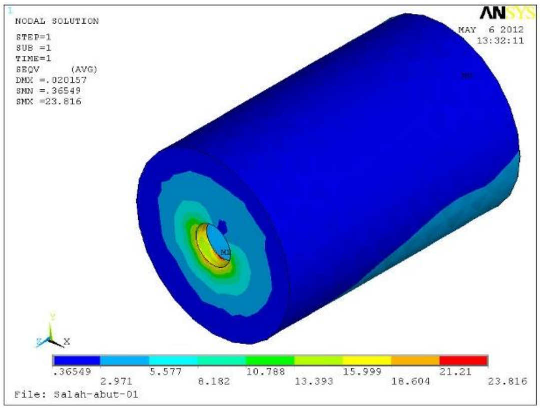
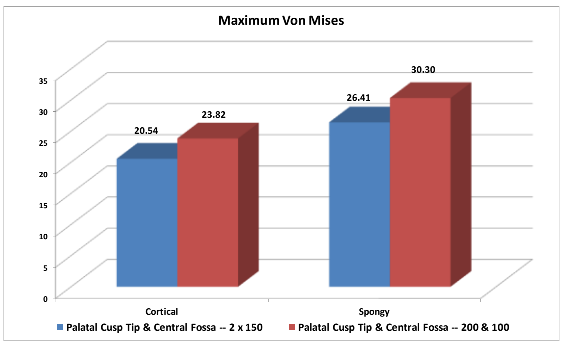


Figure 5: Von Mises stress of cortical bone under Porcelain fussed to metal, and Zinc phosphate cement layer with (a) equal and (b) unequal distributed vertical loading of 300 N. (R53, 54)

(a)



(b)

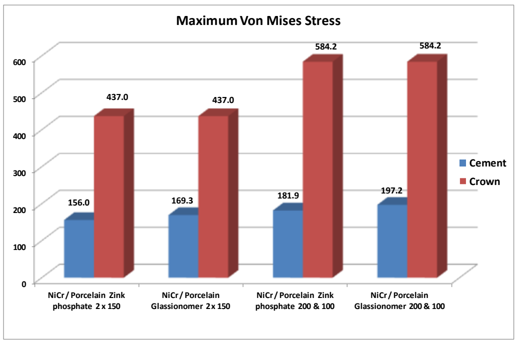


Figure 6: Comparisons (a) between cortical and spongy bone under the two vertical loading cases (b) between different loading conditions on different cement types supporting PFM crown

DISCUSSION:

In implant-supported fixed partial dentures, the stresses occur as a result of functional forces transmitted to the supporting bone by restorative material, abutment, and implant and cannot be moved by external forces or change its position. This in contrary to tooth-supported Crown or fixed partial dentures, the stresses are transmitted to the supporting bone by the restorative materials and maintained by periodontal tissue as a shock-absorbing mechanism transmitted the stress to the bone tissue similarly. So, the stress transmitted to implant, components, and adjacent bone tissue should be protected by a precise fit between prosthesis and implant and the correct selection of framework and veneering materials.[29]

The stresses created because of functional forces affect the masticatory system and biomechanical properties of restorative materials. For this reason the stresses in materials and supporting tissues must be analyzed. The generated Stresses can be controlled by idealization of geometry, material properties, supporting bone, and loading conditions [30,31]. In the present study, a finite-element stress analysis method was used to evaluate the stresses generated in the abutment, implant, and supporting bone with various materials used in implant-crown design under functional forces.

The model used in this study implied several assumptions regarding the simulated structures. The structures in the model (as crown, cement layer, implant complex, and bone) were all assumed to be homogeneous and isotropic and to possess linear elasticity. Additionally, implant–bone interface was established (complete osseointegration), which does not necessarily simulate clinical situations [32, 33]. In addition, it is important to point out that the stress distribution patterns may have been different, depending on the materials and properties assigned to each layer of the model used in the experiments. Thus, the inherent limitations in this study should be considered. Hojjatie and Anusavice [34] also accepted all materials as linear elastic, homogeneous, and isotropic, and ignored cement thickness in their finite-element stress analysis study.

Due to the various materials, components, and protocols used, it is difficult to compare the strengths of cements among the conflicting studies. Therefore, there are no conclusive approvals for identical cementation techniques or the type of cement to use. Additionally, with the large number of available implant systems, cement retention may vary with the different designs, materials, surface treatment, and treatment techniques used by dental laboratory technicians, although a survey was conducted to determine what dental cementation protocols are taught and recommended by 62 US dental schools and postgraduate programs (2010), they reported that Resin-modified glass ionomer cement was most frequently cited as the cement used for inserting implant restorations [35].

Furthermore, in recent study (2015) was carried out to determine the effect of using two cement types, with three different thicknesses, on stress levels and distributions within bone around implant premolar, using three-dimensional Finite Element Analysis techniques, they founded that regardless the cement type, thicker cement layer (60 µm in this study) is preferred to relax cortical bone stresses by about 6.5%. While, spongy bone is insensitive to cement type or its layer thickness [36]. In the current study cement thickness was also ignored because it did not affect the stress distribution.

The design of the occlusal surface of the model can influence the stress distribution pattern. In the current study, the locations for the force applications were specifically described as cusp tip and distal fossa. However, the geometric form of the tooth surface can produce a pattern of stress distribution that is specific for the modeled form. The pattern could be different with even moderate changes to the occlusal surface of the crown. The occlusal form chosen for this model does not mean that the same form would represent all premolar teeth.

The same occlusal phenomenon was used to evaluate the effect of various materials on stresses transferred to supporting bone, implant, and abutment for all models. In the current

study four different loading conditions by applying vertical and oblique loading as; two forces at Palatal Cusp Tip and Central Fossa each of 150 N, and two forces at Palatal Cusp Tip and Central Fossa as 200 and 100 N respectively [37].

Several studies investigated the effects of different occlusal materials on implants. Bassit et al [38] demonstrated that using different occlusal surface materials does not produce different stresses in implants. Cibrika et al. [1] did not observe a significant statistical difference when they used resin, gold, and ceramic as occlusal surfaces. However, in the current study different occlusal surface materials and frameworks generated approximately similar stresses in implants but differences in stress related to crown material and framework. The reason for these discrepancies may result from the differences between materials used in the current study and the other studies.

When the stress distribution in porcelain structure was investigated, In-ceram alumina porcelain crown material showed the highest stress concentration. The high stress value in porcelain was the result of the force applying structure. When the stress distribution in framework was investigated, the stress values were different for each model. The reason of these differences may be that the elasticity modulus of In-Ceram alumina was higher than porcelain fused to metal and zirconia crowns. For this reason, Structural differences in frameworks affected the stress distribution in implant structure.

Gomes et al. [39] evaluated the effect of different material combinations (GP, porcelain fused to gold alloy; GR, modified composite resin fused to gold alloy; TP, porcelain fused to titanium; TR, modified composite resin fused to titanium; and ZP, porcelain fused to zirconia). A 100-N vertical force was applied to the contact points of the crowns on stress distribution within metal-ceramic and all-ceramic single implant-supported prostheses by three-dimensional finite element analysis .they concluded that the use of different materials to fabricate a superstructure for a single implant-supported prosthesis did not affect the stress distribution in the supporting bone. Thus, when choosing materials for implant-supported prostheses the clinician should choose the one that will create less tension on the implant and surrounding tissues. His result is in agreement with the findings of the current study.

Moreover, Sevimay et al. [40] investigated the effect of different occlusal surface materials (IPS Empress 2, In-Ceram, PFBM, PFNM) on stress generation under functional forces. When using vertical loading at two locations, they concluded that using more rigid or resilient material for the superstructure of an implant-supported prosthesis did not have any effect on stress distribution and stress values at the bone tissue surrounding implant. However, in the abutment and crown structure, stress distributions and localizations were affected by the material' s rigidity. His result is in agreement with the findings of the current study When the stress distribution in supporting bone related to the load direction was investigated, Vertical equal loading on crown reduces cortical bone Von Mises stress (about 20.5 MPa) by about 14%, in comparison with unequal loading (about 23.8 MPa).

A consistent observation from all models was concentration of maximum stresses at the porcelain surface at the loading points. For this reason, interceptive occlusal contact in the crown should be eliminated and proper occlusal relationship should be provided. The materials selected for the occlusal surface of the implant-supported prosthesis may affect the transmission of forces and the maintenance of occlusal contacts

Papavasiliou et al. [41] investigated the effect of the osseointegration degree to stress distribution and found higher crestal stresses than apical stresses under all conditions. In the current study, the stresses were concentrated in the neck of the implant due to the rigid connection between the implant and the bone. The elasticity module of cortical bone is higher than spongy bone; for this reason, cortical bone is stronger and more resistant to deformation [42–44].

In the light of the results of the present study, physical and mechanical properties must be considered in addition to esthetic and biological properties when one is selecting restorative materials. The selection should be customized for the individual case for optimum esthetics and performance. It must be kept in mind that the laboratory techniques and design properties of restorations are also determining factors on final success.

One of the limitations of this study is the simplified geometry of the bone model. In addition, the material properties of the FE model were assumed to be isotropic and homogenous. The consideration of the anisotropic and inhomogeneous properties is still needed in future studies. Another limitation was the use of a static occlusal force in the FE simulations. Although oblique loading has been suggested to represent a realistic occlusal load, [4] chewing movement, especially with dynamic loading simulations, needs to be considered in future investigations. Additionally, 100% implant-bone interface was established, which does not necessarily simulate clinical situations. Also, the stress distribution patterns simulated may be different depending on the materials and properties assigned to each layer of the model and the model used in the experiments. Thus, the inherent limitations in this study should be considered.

CONCLUSIONS:

Within the limitations of this study, the following points can be concluded;

1- In-Ceram crown induced higher value of Von Mises stress than zirconium, and Porcelain fussed to metal, which are fairly similar.

2- Equally distributed vertical loading at Palatal Cusp Tip & Central Fossa reduce total deformation and Von Mises stress on crown and implant/abutment complex in comparison to unequal distribution.

3- Equally distributed vertical loading at Palatal Cusp Tip & Central Fossa reduce Von Mises stress on cortical and spongy bone in comparison to unequal distribution.

4- Zinc-phosphate cement type receives less stresses and deformations than Glass ionomer, while both failed under oblique loading by 300 N, during supporting PFM crowns.

5- Using more rigid or resilient material for the superstructure of an implant-supported prosthesis did not affect the stress distribution and its values at the bone tissue surrounding implant. However, in the abutment and crown structure, stress distributions and its' extremes positions were affected by the material's rigidity.

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