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# Influence of Geometric Design Variable and Bone Quality on Stress Distribution for Zirconia Dental Implants-A 3D Finite Element Analysis

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**Abstract:** This study aims to investigate the effects of variable thread pitch on stress distribution in bones of different bone qualities under two different loading conditions (Vertical, and Horizontal) for a Zirconia dental implant. For this purpose, a three dimensional finite element model of the mandibular premolar section and three single threaded implants of 0.8 mm, 1.6 mm, 2.4 mm pitch was designed. Finite element analysis software was used to develop the model and three different bone qualities (Type II, Type III, and Type IV) were prepared. A vertical load of 200 N, and a horizontal load of 100 N was applied at the abutment surface. The von-Mises stress criterion was used to analyze the results. The crestal bony-region of the mandibular section was subjected to maximum von-Mises stresses for all bone qualities. The outcome of this study indicates that, horizontal loading had more influence on stress distribution than vertical loading, regardless of the bone qualities and pitch values. Varying the dental implant pitch does not cause any decrease in stress distribution in bone, when the bone density decreased. The study concluded that implants with minimum pitch values induced lesser stress values at the implant-bone interface.

**Keywords:** Bone quality, finite element analysis, implant, stress.

## 1 Introduction

Dental implants are commonly used to replace missing or damaged teeth in fully and partly edentulous patients [Papaspyridakos, Mokti, Chen et al. (2014); Pjetursson, Thoma, Jung et al. (2012)]. The existence of dense fibrous connective tissue between the cementum and alveolar bone with natural teeth, acts as a cushioning element to shield occlusal loads. The details of dental implant are shown in Fig. 1. In the case of osseointegrated dental implants, the static and dynamic loads are transferred directly to the nearby bone in patients treated with an implant. These kinds of loads could induce failure of the implant, a rupture in the bone and implant interface, slackening of the implant-abutment system and unwanted bone tissue resorption [Eskitascioglu, Usumez, Sevimay et al. (2004)]. Hence, it is important to consider the interplay between the bone and the implant, and their connections to the nearby components for the success of osseointegration, and studying the biomechanical comportment turns out to be an

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important factor for the suitable performing of implants [Lin, Wang and Chang (2008); Chen, Chen, Chang et al. (2014)].

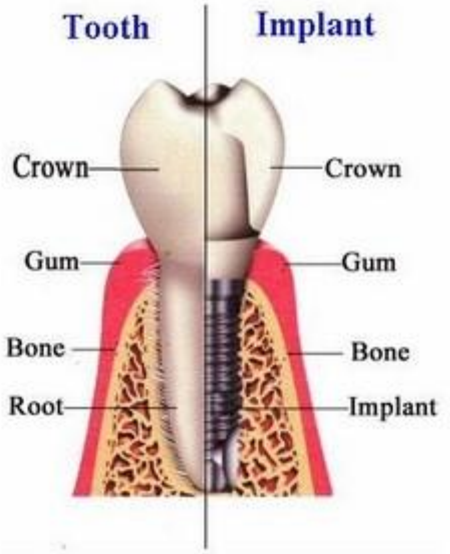

**Figure 1:** Details of dental implant with natural teeth

Many researchers have focused on maximizing the contact area, and minimizing the stress on the bone-implant interface so that bone resorption can be reduced. Efforts have been made to maximize the contact area on altering the variable geometry parameters of the dental implants [Chun, Cheong, Han et al. (2002); Tada, Stegaroiu, Kitamura et al. (2003)]. These studies analyzed the importance of thread design, which is a significant factor for optimizing the dental implants. It has been found that the success of dental implants is influenced by many biomechanical factors comprising, the type of load, and surface characteristics of the implant, implant geometry, and functioning of the surrounding bone [Brunski, Block, Kent et al. (1997)]. The transferring of the load to the adjoining bone is affected by many parameters, such as the length, diameter of the implant, pitch, and depth of the thread [Li, Hu, Cheng et al. (2011); Lee, Lin, Kang et al. (2010)]. The threads are used to maximize the initial contact, improve initial stability, enlarge implant surface area [Ivanoff, Grondahl, Sennerby et al. (1999)] and favor the dissipation of interfacial stress [Huang, Chang, Hsu et al. (2007)]. Moreover, many geometric variables like thread depth, thickness, helix angle, face angle, and pitch can be varied to modify the functional thread surface and to influence the effect of the load distribution mechanism of the implant [Misch (2005)]. Among these thread parameters, thread pitch is considered as an important variable since it has a more clinical significance for an operation which could also influence the speed of implantation and operating convenience [Misch (2005)].

Bone quality is another important factor which determines the success rate of the dental implants. A strong interface between the bone and the implant should be accomplished in order to improve the success rate of implants. Further, the internal structure of the bone reflects its quality and also the different variations in its elastic and mechanical potency

[Misch (1990); Misch (2007); Sevimay, Turhan, Kilicarslan et al. (2005)]. In general, bone quality is an essential factor in determining implant selection, as per surgical protocols [Ashman and Van Buskirk (1987)]. The classification of bone quality proposed by [Lekholm and Zarb (1985)] has since been recognized by clinicians and researchers as a paradigm in evaluating patients for implant emplacement. Accordingly, the quality of the bone has been classified into four types on the basis of its radiographic appearance, and jawbone quality. Hence, it is important to understand the behavior of the bone around the implants to study the biomechanics of the dental implant.

The material chosen for dental implants is titanium due to its excellent physical and mechanical properties, and also titanium has good compatibility with living tissue. However, the titanium dental implant may cause aesthetic problems due to its color which is considered as one of the disadvantages. Hence, ceramic material is used to overcome this aesthetic issue, as it has high biocompatibility, and is able to sustain the load acting on the implant; Zirconia is a good material choice for dental implants to replace titanium [Prithviraj, Deeksha, Regish et al. (2012); Depprich, Zipprich, Ommerborn et al. (2008)]. Despite that, the report available on stress distribution for Zirconia dental implants is found to be less [Çaglar, Bal, Karakoca et al. (2011); Chang, Chen, Yeung et al. (2012)]. Moreover, the influences of pitch and bone quality on stress distribution for Zirconia dental implants are not well reported. Hence, the purpose of the current study is to analyze the effect of distinct thread pitch and distinct bone qualities for Zirconia dental implants on stress distribution in cortical, cancellous bone using the three dimensional finite element analysis, which is a numerical tool widely used in dentistry to analyze the stresses and strains in cortical, cancellous bone and also because it helps researchers to predict the stresses and strains in other regions of the implant-bone model structure.

## 2 Materials and methods

### *2.1 Three-dimensional finite element modeling*

Computer aided design software was used (SolidWorks Corp; Concord, MA, USA 2016) to design the models of the mandibular premolar segment and a screw shaped dental implant with abutment as shown in Fig. 2. The single threaded thread geometry of the V shape cylinder screwed implants (3.7 mm diameter, 10 mm length, 0.3 mm collar height, helix angle=60°), were designed with three different pitch values of 0.8 mm, 1.6 mm, and 2.4 mm. The diameter of the implant is 3.7 mm. The bone-implant models were designed for three different bone qualities (type II, type III, and type IV) in line with [Lekholm and Zarb (1985)]. In type I bone quality, the entire jaw is composed of homogeneous cortical bone and hence, type I bone is not considered in this study. In type II bone a thick layer of cortical bone with a thickness of 2 mm surrounds a core of dense cancellous bone; in type III bone a thin layer of cortical bone with a thickness of 1 mm surrounds a core of dense cancellous bone; and type IV bone is characterized by a thin layer of cortical bone with a thickness of 1 mm surrounding a core of low dense cancellous bone. The bone-implant interface is shown in Fig. 3. The model of the bone-implant structure was meshed in hypermesh software (Altair Engineering, Troy, MI, USA) using first order four-node tetrahedral elements. The number of elements and nodes are listed in Tab. 1.

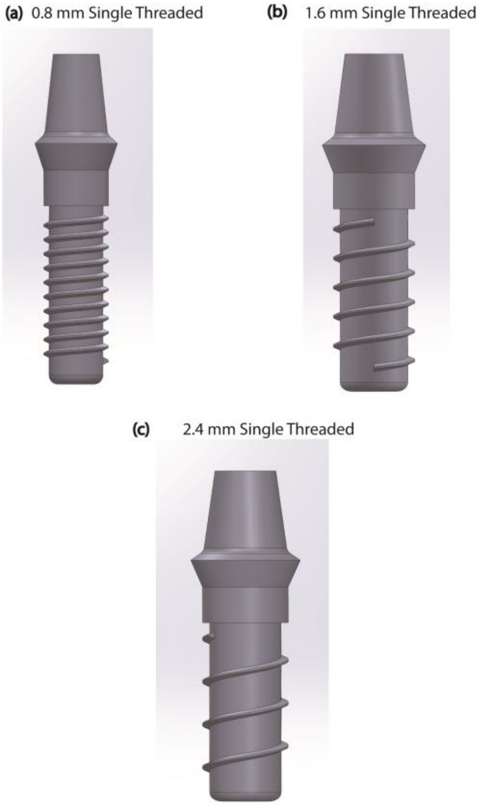

**Figure 2:** Geometry of the implants

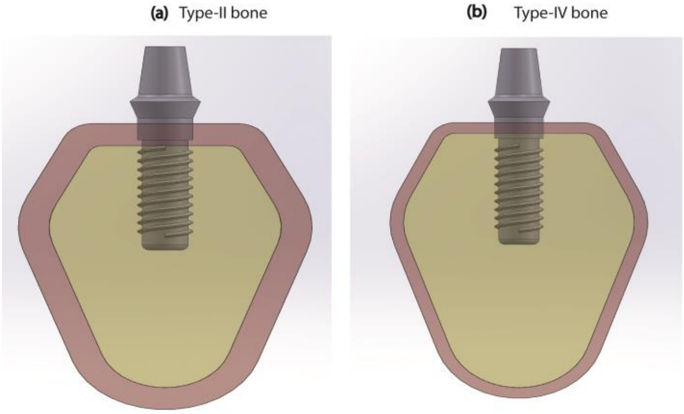

**Figure 3:** Bone-implant interface

**Table 1:** Number of elements and nodes meshed for each thread design

| Thread type | Pitch (mm) | Bone type | Elements | nodes |
|---|---|---|---|---|
| Single threaded | 0.8 | Type II | 575512 | 118774 |
| | | Type III, Type IV | 660953 | 132671 |
| Single threaded | 1.6 | Type II | 666401 | 132149 |
| | | Type III, Type IV | 640966 | 127723 |
| Single threaded | 2.4 | Type II | 670158 | 132265 |
| | | Type III, Type IV | 643307 | 127580 |

### 2.2 Material properties

All the properties used in this study were taken as isotropic, homogeneous, and linear elastic. The elastic properties of the bone and implant were taken from the literature [Holmes and Loftus (1997); Guazzato, Albarky, Ringer et al. (2004)] as shown in Tab. 2.

**Table 2:** Material properties

| Materials | Young's modulus (GPa) | Poisson Ratio | Density (Kg/m$^3$) | Yield value (MPa) |
|---|---|---|---|---|
| Cortical bone | 13.7 | 0.3 | 1100 | 114 |
| Dense cancellous bone | 1.37 | 0.3 | 1000 | 10-20 |
| Low dense cancellous bone | 0.231 | 0.3 | 270 | 10-20 |
| Zirconia | 210 | 0.24 | 5000 | 230 |

### 2.3 Interface conditions

A perfect contact was considered between the bone and implant. The contacts between all dissimilar structures were bonded while considering the linear analysis. The contact between compact bone and trabecular bone was yet considered as bonded in non-linear analysis, however the contact between the implant and other region of the bone was set to be a frictional contact based on the Coulomb's friction law. The coefficient of friction at the implant-bone interface relies on the magnitude of the applied force and the chemical composition of the material. In cases which the involves the use of Zirconia material as a biomaterial for manufacturing dental implants, a coefficient of friction of about 0.25 to 0.3 is recommended [Shockey, Fraunhofer and Seligson (1985); Rancourt, Shirazi-Adl, Drouin et al. (1990); Shacham, Castel and Gefen (2010)]. Therefore, we used a coefficient of friction of 0.3 at the bone-implant interface and the nonlinear frictional contact elements (CONTACT 174) were considered to simulate the bone-implant interface [Winter, Klein and Karl (2013)]. Hence the FEA model was designed by using non-linear frictional contact element in order to get primary stability for the immediate loading conditions.

### *2.4 Constraints and loads*

The bone-implant models were constrained in all directions at the nodes on the mesial, distal and bottom surfaces as shown in Fig. 4. in accordance with a previous study [Wu, Chen, Yip et al. (2012)].

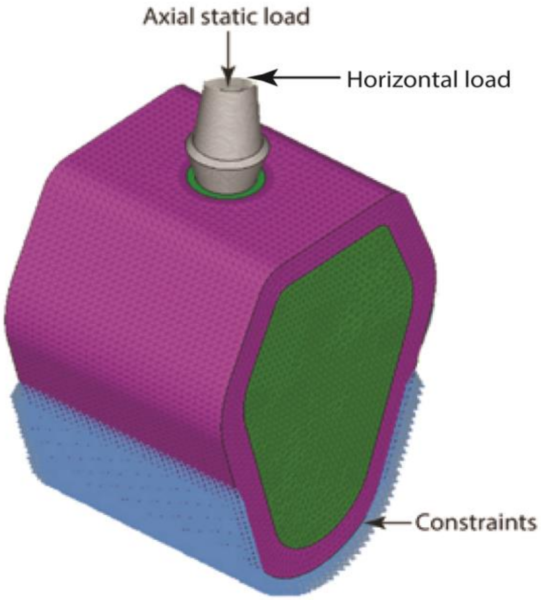

**Figure 4:** Constraints and loads

An axial compressive load of 200 N corresponds to the mean peak occlusal load for fixed partial dental prosthesis [Mericske-Stern, Assal, Mericske et al. (1995)] supported by implants in the molar region, and the calculated lateral load in the molar region is half of the axial load [Graf, Grassl and Aberhard (1974)]. Hence, in this study a vertical load of 200 N, and a horizontal load of 100 N was applied axially, and bucco-lingually at the center of the abutment surface.

## 3 Results

### *3.1 Mesh of convergence*

A mesh convergence study was performed to ascertain the prediction accuracy of the FE model was not affected by the chosen mesh element size. The resulting convergence criterion of less than 2% change in peak displacement of the implant between the numbers of elements in mesh at a given load was observed. (Figs. 5a, 5b).

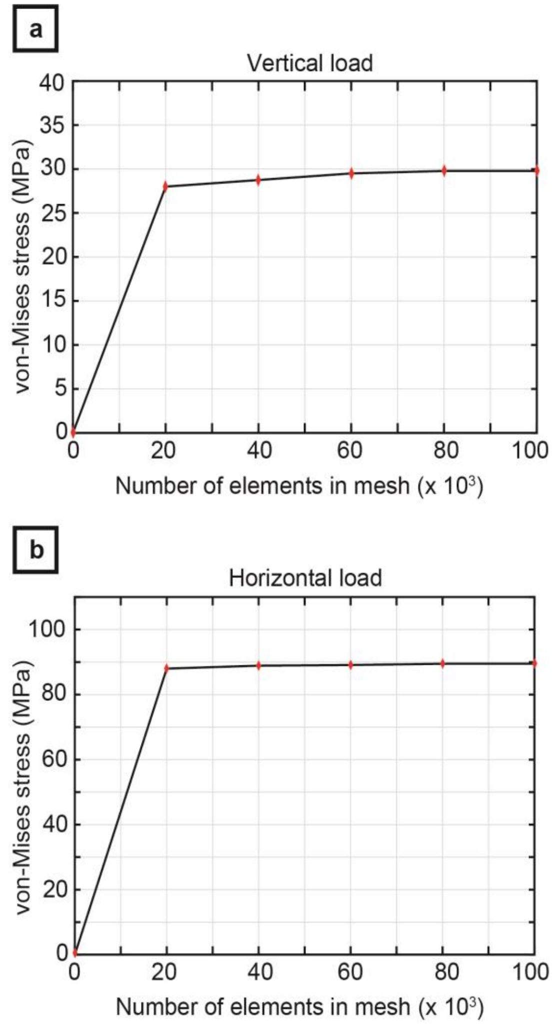

**Figure 5:** Result of convergence study in the single threaded dental implant with 0.8 mm pitch in type II bone

### *3.2 Stress analysis in bone*

The results were compared between three distinct pitches and three distinct bone qualities. The maximum von-Mises stresses observed in cortical bone, and cancellous bone under axial, and horizontal load for three different bone qualities, and three different pitches are listed in Tab. 3 and Tab. 4.

### *3.3 Vertical load*

In cortical bone, regardless of the implant pitch, the maximum von-Mises stresses were noticed in type II, and type IV bone qualities for vertical load. The stress distribution for 0.8 mm pitch single threaded implant in cortical bone for different bone qualities is shown in Fig. 6. It has been observed that the maximum stresses were positioned around the neck of the implant for all the bone qualities. The obtained von-Mises stress is minimum for type III bone quality regardless of the implant pitch considered.

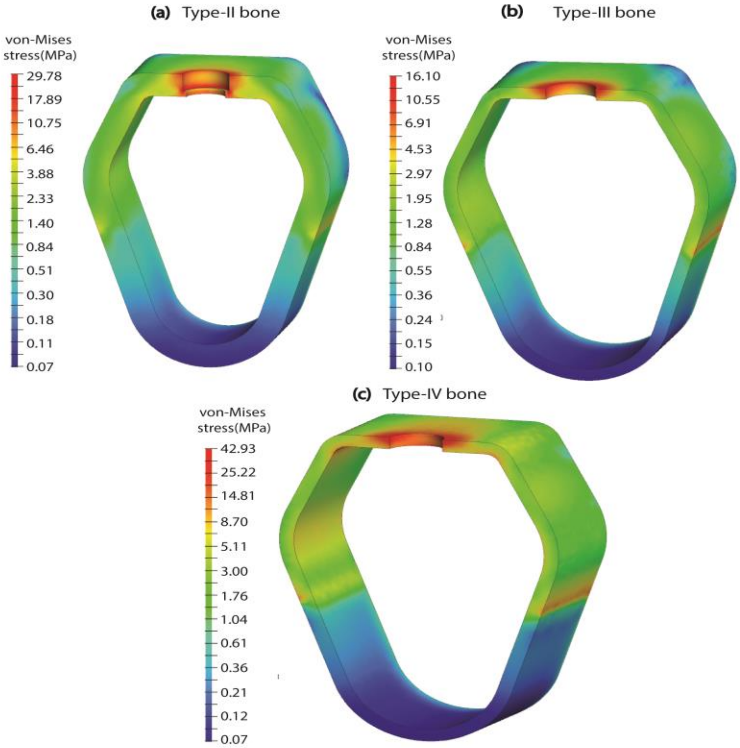

**Figure 6:** von-Mises stress distribution in cortical bone for 0.8 mm pitch

**Table 3:** von-Mises stress in cortical bone

| Thread design | Type II | | Type III | | Type IV | |
|---|---|---|---|---|---|---|
| | von-Mises stress (MPa) | | | | | |
| | Vertical Load | Horizontal Load | Vertical Load | Horizontal Load | Vertical Load | Horizontal Load |
| Single threaded 0.8 mm pitch | 29.78 | 89.48 | 16.1 | 106.77 | 42.93 | 148.22 |
| Single threaded 1.6 mm pitch | 37.21 | 95.89 | 15.68 | 102.02 | 68.01 | 153.97 |
| Single threaded 2.4 mm pitch | 42.26 | 91.95 | 16.48 | 104.78 | 66.46 | 156.8 |

In addition to this, comparing the 0.8mm pitch single threaded implant with the 1.6 mm, 2.4 mm pitch single threaded implant, the stress is increased by 24.8%, and 42% in type II bone. The stress is decreased, and increased by 2.5% in type III bone for 1.6 mm, 2.4

mm pitch single threaded implant when compared with the 0.8 mm pitch single threaded implant. However, no significant percentage difference is obtained for type IV bone qualities. It has been found that, the stress is increased by 58.5%, and 54.7% in type IV bone for 1.6 mm, and 2.4 mm single threaded implants when compared to the 0.8 mm pitch single threaded implant in type IV bone.

**Table 4:** von-Mises stress in cancellous bone

| Thread design | Type II | | Type III | | Type IV | |
|---|---|---|---|---|---|---|
| | von-Mises stress (MPa) | | | | | |
| | Vertical Load | Horizontal Load | Vertical Load | Horizontal Load | Vertical Load | Horizontal Load |
| Single threaded 0.8 mm pitch | 27.52 | 13.72 | 58.92 | 24.48 | 45.77 | 15.13 |
| Single threaded 1.6 mm pitch | 41.23 | 29.26 | 90.27 | 22.68 | 100.7 | 14.36 |
| Single threaded 2.4 mm pitch | 48.09 | 40.44 | 88.5 | 21.87 | 82.4 | 13.13 |

In cancellous bone, the maximum von-Mises stress was observed in type III, and type IV bone qualities, and type II bone quality induces minimum von-Mises stresses regardless of the variation in pitch. The stress distribution for 0.8 mm pitch single threaded implant in cancellous bone for different bone qualities is shown in Fig. 7. The stress is increased by 49.8%, 74.9%, 53.1%, 50.2%, 119.9% and 80 % in type II, type III, and type IV bones respectively, when comparing the 0.8 mm pitch single threaded implant with the 1.6 mm, 2.4 mm pitch single threaded implant.

### *3.4 Horizontal load*

In cortical bone, the von-Mises stress is found to be the minimum in type II bone quality, and type III, and type IV bone qualities induced the maximum von-Mises stresses regardless of the variations in pitch considered in this study. Under the influence of horizontal load, the stress is increased by 7.2%, 2.8%, 3.9% and 5.8% in type II, type IV bones; moreover, the stress is decreased by 4.5% and 1.9% in type III bone when comparing the 0.8 mm pitch single threaded implant with the 1.6 mm, 2.4 mm pitch single threaded implants.

In cancellous bone, the stress is increased by 113%, 194.6% in type II bone quality, 7.4%, and 10.6% in type III bone quality and when comparing the 0.8 mm pitch single threaded implant with the 1.6 mm, 2.4 mm pitch single threaded implant. Also, it is decreased by 5.3% and 13.2% in type IV bone qualities for the same thread pitch value.

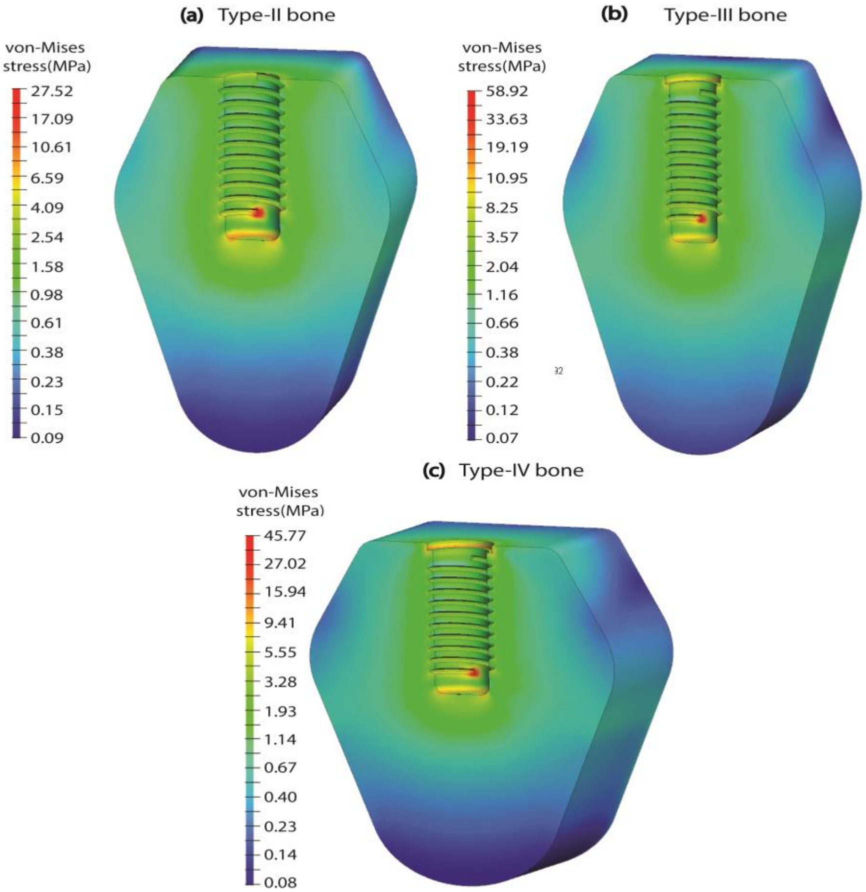

**Figure 7:** von-Mises stress distribution in cortical bone for 0.8 mm pitch

## 4 Discussion

The survival rate of dental implants is associated with many factors; bone quality and implant thread profiles are two of them. It has been reported that, type IV bone quality is considered as a weaker bone as it has poor biomechanical stability, and the bone implant contact area is found to be less, hence, its load transferring capacity at the bone-implant interface is also weak [Misch (2007)]. The advancement in dental implant thread design leads to several advantages, including the enhancement of dental implant stability, distribution of stress at the bone-implant interface, and an increase in the surface contact area of the implants [Çaglar, Bal, Karakoca et al. (2011)]. Also, due to variations in strength between the bones (type I to type IV), implants with different designs are required for different bone qualities. In addition to this, the functional surface area is not similar to the bone qualities from type I to type IV. Therefore, it is important to choose a suitable dental implant thread profile based on the bone quality for obtaining better results. Additionally, the biomechanical performance of dental implants has been influenced by several implant thread design variables. The load transferred to the adjacent bone, and dispersion of stress in the bony region and implant, is affected by the thread geometry in the figure of width, depth and pitch [Abuhussein, Pagni, Rebaudi et al. (2010)]. Hence, the present study is focused on bone quality and thread pitch as parameters and the influence of bone quality and pitch on stress distribution in the bony region was examined using a 3D finite element study for a single threaded pitch with 0.8 mm, 1.6 mm and 2.4 mm, and three different bone qualities.

Considering the limited experimental capabilities in the dentistry field, FE analysis is considered as an opportune method for assessing micromotion at the bone-implant interface [Winter, Mohrle, Holst et al. (2010); Winter, Steinmann, Holst et al. (2011)]. FE simulations can provide necessary information (both qualitative and quantitative) to study the biomechanical behaviour of dental implants [Shamami, Karimi, Beigzadeh et al. (2014a); Shamami, Karimi, Beigzadeh et al. (2014b)]. Be that as it may, a few suppositions should be made to simulate real conditions, and these can prompt distortion of the FE model. The validity of FE model is reliant on the geometry, material properties, contact conditions, boundary conditions, and loading conditions [Shriram, Kumar, Cui et al. (2017a); Shriram, Parween, Lee et al. (2017b)]. The contact at the bone-implant interface is very consequential, especially for the loading conditions we considered in this study (immediate loading) [Murakami and Wakabayashi (2014)]. Most FE based studies in the dentistry field have simulated friction elements at the bone-implant interface [Kao, Gung, Chung et al. (2008); Tu, Hsu, Fuh et al. (2010); Sugiura, Yamamoto, Horita et al. (2017)]. Therefore, in this study, the contact at the bone-interface interface was modelled using friction elements. Since material properties likewise have a vital effect on the result, the elastic modulus (Young’s modulus) for type IV cancellous bone was taken from preoperative patient data based on lab tests [Sugiura, Yamamoto, Kawakami et al. (2015)].

The accuracy of results obtained from the FE model is reliant on the FE mesh used. In this study, HyperMesh was used to create a high-quality mesh by following a two-step meshing process. In the first step, two-dimensional surface elements were created by meshing the line into elements. In the second step, three-dimensional elements were created from two-dimensional surface elements. Most FE based studies in the biomedical engineering field have used the main solver (ANSYS or ABAQUS) to create FE mesh [Shamami, Karimi, Beigzadeh et al. (2014a); Shamami, Karimi, Beigzadeh et al. (2014b); Shriram, Kumar, Cui et al. (2017a); Shriram, Parween, Lee et al. (2017b); Murakami and Wakabayashi (2014); Tu, Hsu, Fuh et al. (2010); Sugiura, Yamamoto, Horita et al. (2017)]. We manually inspected the FE mesh model created by ANSYS and found irregular and deformed elements, while the FE mesh model created by HyperMesh was free from irregular and deformed elements. A mesh sensitivity study was performed to ascertain the prediction accuracy was not affected by the number of elements used in the mesh as shown in Figs. 5a, 5b.

It is observed that, no detailed indication is available in the literature related to the types of stresses that must be used for calculations. Nevertheless, a few studies used principal and von-Mises stresses. In line with the existing details, the current study used the maximum failure criterion to determine the stresses; hence, the von-Mises stress evaluation is adopted for calculations [Dundar, Topkaya, Solmaz et al. (2016); Okumura, Stegaroiu, Kitamura et al. (2010)]. The results are listed in Tab. 4 and Tab. 5.

The outcome of this study indicates that, the direction of loading, pitch variable and bone qualities are the main factors to influence the stress distribution in a bony segment. The highest stress values were perceived in horizontal loading, and, the lowest stress values were observed in vertical loading for all values of pitch, and bone qualities in cortical bone. However, this condition is reversed in cancellous bone; the maximum stress values were observed in vertical loading and the magnitude of stress was minimum in horizontal loading. Hence, it can be concluded that horizontal loading is a vital factor of the influence of stress distribution in cortical bone.

The stress in the cortical bone is higher than the stress in the cancellous bone and the magnitude of stress is increased with the implant pitch for all bone qualities. It shows that the distribution of stress is affected by increasing the dental implant pitch for all types of bone qualities. A different result is observed when vertical load is acting on the implant, and under this loading condition the distribution of stress is found to be the maximum in cancellous bone than in cortical bone for all qualities of the bone. Hence, placing implants with different pitches in different bone qualities has generated dissimilar results in the bony region for horizontal and vertical loading.

The results indicate some notable variations in the biomechanical performance of cortical, cancellous bone in accordance with pitch variation. This finding had good agreement with previous studies which reported that the distribution of stress from the implant to the bone is affected by the implant thread profile, and geometry of the implant [Akpinar, Demirel, Parnas et al. (1996); Holmgren, Seckinger, Kilgren et al. (1998)]. Clear information from the literature shows that the implant pitch is a crucial factor to reduce or minimize the peak stresses at the bony-implant region [Abuhussein, Pagni, Rebaudi et al. (2010)]. For example, the three dimensional finite element analysis [Motoyoshi, Yano, Tsuruoka et al. (2005)] on a titanium implant indicates that the decrease in thread pitch leads to reduce the maximum stress concentration in the bony region. Moreover, the thread pitch with 0.8 mm is an optimal pitch value and this value has a positive correlation to reduce the stress concentration, and maintain the initial stability of the implant [Kong, Liu, Hu et al. (2006)]. These findings are consistent with the finding of this study, where zirconia is used as the implant material, and among three different pitch values, the 0.8 mm pitch single threaded implant gives minimum stress values compared with the other pitch values (1.6 mm, 2.4 mm). Regardless of the bone quality, and implant pitch, the maximum von-Mises stresses were concentrated at the crestal bony region and the finding of this work is in line with the published 3D FEA on titanium implant [Lin, Kuo and Lin (2005), which shows that, bone loss happens in the implant neck region, since, the maximum amount of stress was concentrated in the crestal bony region. Hence, it can be seen that changing the implant material will not influence the stress concentration area.

The finding of this study also shows a negative correlation between bone qualities and stress generation. Decrease in bone density (type II>type III>type IV) will increase the stress distribution in the bony region. This finding is consistent with reported literature [Sevimay and Turhan (2005)] which described the influence of bone quality on stress distribution in an implant-supported crown for constant pitch. Hence, varying the dental implant pitch does not cause any decrease in the stress distribution in bone when the bone density decreased.

Furthermore, it is important to transfer occlusal loads effectively to the bone implant interface, and the load transferring mechanism of the implant is affected by the functional surface area of the implant body. The functional surface area of the implant body depends on thread design factors like pitch, depth, and width [Misch (2005)]. Hence, the implant surface area must be improved by designing the implant with more number of pitches for proper stress distribution. Due to this, favorable stress distribution occurs in cancellous bone rather than cortical bone, since the interface of the thread pitch with the cortical bone is found to be less, and this concept is in line with the finding of this work.

Additionally, implants with higher pitches require more amount of torque to place an implant into a bone. Hence, this may be the reason to produce more stresses in the bone-implant structure. Hence, it is suggested to use implant thread pitches less than 1.6 mm to minimize the stress value at the bone-implant region. In addition to the implant thread pitch, another thread parameter should also be considered in order to study the biomechanical performance of the implant and bone.

There are several limitations in this study. The FEA model in this study was assumed as homogeneous and isotropic. However, the properties of living tissue are entirely different; for instance, bone behaves as if it is transversely non-homogeneous. Also, in this study, the effect of the crown is not considered. Hence, the result of this study must be viewed carefully, and the limitations of this study should also be considered when applying these results to clinical settings.

## 5 Conclusion

In this study, the influence of thread pitch, and bone quality on stress distribution in the bony region was analyzed, using Zirconia as a dental implant material. Apart from the limitations considered, the outcome of this study gives some important findings on stress distribution in the bony region for different pitch values.

1. The finding of this study shows that, irrespective of the bone quality, loading is the important factor in stress distribution in the bone.

2. Significant variations are observed in stress distribution when the implant thread pitch is increased. Hence, implant thread profile must be considered for a proper distribution of the stress to the bony segment.

3. The study also concluded that changing the implant material will not influence the stress concentration area.

4. The Implant thread pitch with more than 0.8 mm generates the maximum amount of stress in the bone-implant structure. Varying the dental implant pitch does not cause any decrease in the stress distribution in bone when the bone density decreased.

5. Zirconia as a dental implant material has gained attention recently. Hence, further research is required to know more about the impact of materials on stress distribution in the bone-implant structure for variable thread pitch values.

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