Studying the biomechanical effects of zirconia implant geometry and bone quality on the bone-implant interface using finite element analysis

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The success of dental implants is influenced by several biomechanical factors such as implant design, bone quality, length of the implant, and the load transferred to the implant. The present studyaimsto determine the effects of bone quality, implant length, and bone type on stress/strain distribution in bone and implant for a zirconia implant. The study was performed using the three dimensional finite element analysis and four different lengths, two types of implants, and four different bone qualities. The Elastic modulus of a cancellous bone was varied to represent the four different bone qualities. A load of 100 N was applied at the center of the abutment. The result of this current work shows that a bone is subjected to the maximum equivalent stress and strain when the cancellous bone density decreased. The screw type implant induced lesser strain than the cylinder type load. The study also confirms that longer implants produced lesser stain than shorter implants, and type I, and II bones induced lesser stresses than type III, and IV bones. The importance of bone quality has been confirmed from this study, and zirconia dental implants have induced lesser stresses.

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1. Introduction

The success of dental implants is related to how the stresses are transmitted to the neighbouring bone. The transmitting load from the implant to the neighbouring bone is governed by many factors like length, diameter and shape of the implant, contact between bone and implant, and the quantity and quality of the neighbouring bone. Hence, it is important to design dental implant geometry to reduce the bone stress so that the minimization of the peripheral bone loss is possible from a bioengineering perspective (1).Many scientific studies assisted the expectedness of dental implant treatment, accounting for the achievement of more than ninety percentage rates for various implant structures (2, 3). Moreover, these studies recorded the peripheral bone loss which happens around the dental implants that persisted for years (3). The incidence of peripheral bone loss is regularly attributed to deprived oral hygiene (4-6) and several biomechanical factors (3,5,7-10).The biomechanical factors can be related to the shape, diameter, and length, and the material and surface characteristics of the implant, and also to the bone quality, health condition of the patient and the occlusal force transmitted. Hence, it is important to consider the biomechanical factors in order to lessen the peripheral bone loss.

Different shapes of dental implants are available; they can be implanted in specific positions and continue to be integrated in the patient's bone with the aid of bone regeneration techniques. At present ninety dental implants which are accessible in the market can be used in dental implant surgery (11). The screw type implants and cylinder form implants are the major shapes of the implants used in dentistry. According to the study conducted by Albrektsson et.al (12), the larger bone loss is found around the cylindrical implant than the screw type implant. The implant length is another key factor which is contributes to implant failure. The shorter implants may be assumed to produce larger stress, and strain in the bone, because implant length is

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connected with the implant-bone interface area, and therefore the shorter implants are more apt to failure (13-16). Bone quality is another important factor which influences the long term survival rate of dental implants. Moreover, a lower success rate is caused by the poor quality of bone around the implants. The patient's bone for implant placement will be evaluated based on the classification suggested by Lekholm and Zarb (17) which has been widely recognized by clinicians. According to the study conducted by Jaffin and Berman (18), it has been observed that the failure rate of the implant is only 3% when it isplaced in type I, II, III bone after five years; at the same time, the failure rate is observed to be 35% for type IV bone. Considering the fact that the bone around the implant should respond to the occlusal loads which produced stresses and strains, the poor quality of bone maysimply fail to resist these loads. Many clinical studies have agreed with Jaffin and Berman; hence poor bone quality leads to more implant failure rates.

Attempts had been made to make a dental implant with the aid of several materials, namely, stainless steel, Co-Cr and Vitallium. The advancement of materials research and technology enhanced the number of materials for dental implant application.Currently, titanium turns out to be the most prominent implant material because of its excellent biocompatibility (19). However, titanium has the disadvantage that it may induce esthetic problems, mainly in the region of thin gingival tissue. Hence, to overcome this issue, ceramic materials were introduced. Nowadays, the research is directed towardszirconia which is one of the most popular ceramic materials and has good mechanical properties, high biocompatibility; in addition to this, a number of studies conducted in animals display the results that, it has as good an osseointegration as that of titanium (20, 21). The Mechanical correlation between different implant lengths and various bone qualities is found to be less in the existing literature. Furthermore, no useful information is found from experimental and clinical studies to study the biomechanics for a complex multi parameter analysis for zirconia as dental implant material. Hence, the present study aims to investigate the effect of the biomechanical response of the bone to various lengths of zirconia implants, shapes and different bone qualities, using the three dimensional (3D) finite element analysis (FEA).

2. Materials and methods

The present study was executed based on a three dimensional finite element analysis, a preferable logical tool used in dental biomechanics research which delivers the mechanical responses in a satisfactory manner. Moreover, the biomechanical behaviour of different geometries of the implant, and the impact of bone qualities on stress/strain distributions can be predicted using FEA. Hence, FEA has been chosen in this analysis. The implant and abutment used in this study were designed with computer aided design software (Solid works 2016).The bone model used in this study was eased as 23.4mm×25.6mm×9mmsymbolizing height×mesiodistal× buccolingual. A Thickness of 2mm was chosen for the cortical bone layer which was surrounded by a core of dense cancellous bone. Screw and cylinder type zirconia implants were interred in the designed bone model. The studied implants were modelled in four different lengths of 9mm, 10mm, 12mm and 14mm respectively. Threads were designed only at the cancellous bone region and not at the cortical bone level, and the diameter of the implant was 4mm at the cortical bone region, and 3.2mm at the cancellous bone region. Furthermore, a cylinder implant with diameters of 4mm, and 3.6mm was chosen for the cancellous bone and cortical bone regions respectively. These dimensions are preferred in order to get an implant of identical volume along with the screw type implant. The materials used in this study are considered as isotropic, homogeneous and linearly elastic, and the Young's modulus of the cortical bone which is equal to 13GPa was referred to from the available literature (22-24). Young's modulus of 210GPa and a Poisson ratio of 0.24 were assumed for the zirconia implant material (25).According to the study conducted by Rho et.al (26) who calculated the Young's modulus of bone with various apparent densities, four types of bone were designed (Type I, II, III and IV) by varying the elastic moduli of cancellous bone as 9.5GPa, 5.5GPa, 1.6GPa and 0.69GPa respectively. The boundary conditions were applied at the distal end surface of the bone section and the nodes of all directions were constrained. The occlusal load of 100N was applied axially at the centre of the abutment.. The maximum tensile stress, compressive stress, von-Mises stresses and corresponding strains were evaluated using FEA in bone and implant.

3. Results

The results were presented based on the stress and strain distribution criterion. The Generated stresses and strains for cancellous, and cortical bone are listed in tables 1 to 4 for all lengths of implant, and bone quality. The distribution of stress for the cylinder type implant of 9mm, and all bone qualities. The result of this study displays that the maximum stresses are situated around the neck of the implant for both cancellous, cortical bone. However, it has been observed that the direction at which the stresses are distributed are found to differ in type I, II and type III, IV bones. For type I, and II bone stress distribution takes place along the mesial, distal direction; however, for type III, and IV it is along buccal and lingual for axial load. The distribution of strain at the cancellous, and cortical bone regions for all types of length of the implant and various bone qualities are listed in tables 3, and 4. The results indicated some variations in strain at the cancellous, cortical bone regions with respect to bone quality and type of implant used. A strain distribution on the cancellous surface for cylinder and screw type implants of length 14 mm is shown in fig 1a for type III bone, and fig 1b for type IV bone, respectively. With respect to cylindric, and screw type implants, it has been found that the maximum strain was observed close to the base of the implant for type III , and type IV bones.

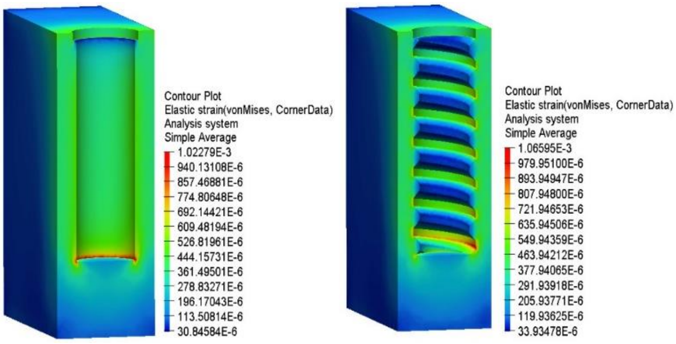

Fig. 1a. EQV strain distribution at cancellous bone region for cylinder, and screw implant type for 14mm length of type III quality bone.

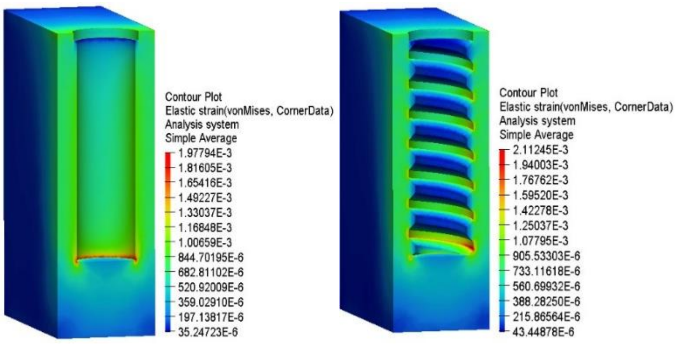

Fig. 1b. EQV strain distribution at cancellous bone region for cylinder, and screw implant type for 14mm length of type IV quality bone.

The strain distribution on the cancellous surface for cylinder and screw type implants of length 12 mm are shown in fig 2a for type II bone, and 2b for type I bone, respectively and the outcome of this indicates that, reasonably high strains were induced at the base of the implant and lesser strain was observed at the neck of the implant and, as shown in fig 7b, for type I bone, strains are generated at the neck area of the implant, but in some incidents it reaches the base region of the implant. The Screw type implant displays a significant variation in strain distribution with respect to different bone qualities. Additionally, the threads generate reasonably sensible strain in the crest region of the thread and around the bone, and fairly dispersed low strain to other regions in the screw type implant. Thus, the threads are used to decrease the degrees of concentration. Moreover, the strain in the cylinder type implant is higher than that in the screw type implant. Also, a smaller length of implant leads to more strain than a larger length of implant.

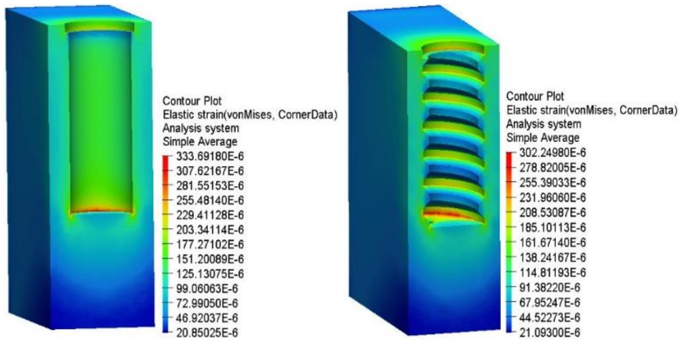

Fig. 2. a EQV strain distribution at the cancellous bone region for cylinder, and screw implant bone type for 12 mm length of type II quality bone.

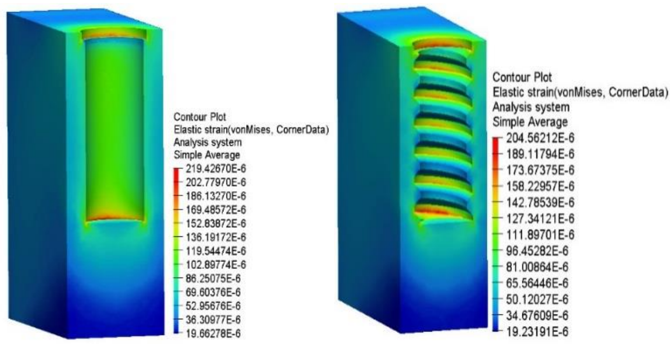

Fig. 2. b EQV strain distribution at the cancellous bone region for cylinder, and screw implant bone type for 12 mm length of type I quality bone.

From Tables 3 and 4 it has been observed that the EQV strain increased regardless of the type, and length of the implant when the density of cancellous bone gets decreased. Furthermore, the maximum equivalent strain has been found in type III, and IV bone quality when the length of the implant gets decreased with respect to the cylinder, and screw type implants.

It has been stated that, the EQV stress at the cortical bone region increased when the density of cancellous bone decreased. However, only a slight difference is found with respect to the implant type. Nevertheless, regardless of the type of implant, it is clear that the maximum EQV stresses are found in type III, and IV bone .Tensile, compressive stresses also increased when the density of cancellous bone gets decreased. The value of these stresses is found to be the maximum in type III, and IV bone qualities, irrespective of the type of implant. The same observation was found in the cancellous bone region with respect to tensile, compressive, EQV stresses.

Table 1. Induced stresses at cancellous, and cortical bones for different implant lengths, and bone qualities for cylinder type implant.

Implant length (mm)	Bone quality	Cancellous bone stresses (MPa)			Cortical bone stresses (MPa)		
		Tensile	Compressive	EQV	Tensile	Compressive	EQV
9	1	1.624	-2.919	2.782	1.850	-9.195	5.680
	2	1.840	-2.889	2.803	2.035	-10.190	6.359
	3	2.033	-2.338	2.469	6.929	-16.133	11.855
	4	1.797	-1.739	1.874	13.815	-24.095	16.853
10	1	1.351	-2.683	2.530	1.831	-8.554	6.297
	2	1.553	-2.666	2.582	2.046	-9.433	6.932
	3	1.919	-2.139	2.340	7.660	-15.267	10.798
	4	1.743	-1.609	1.803	15.412	-21.994	16.246
12	1	1.112	-2.120	2.084	1.907	-8.380	6.042
	2	1.228	-2.141	2.169	2.142	-9.142	6.572
	3	1.703	-1.943	2.282	5.904	-14.481	10.505
	4	1.670	-1.544	1.818	11.532	-21.518	14.417
14	1	0.918	-1.671	1.668	1.812	-8.060	5.676
	2	1.005	-1.721	1.754	2.039	-8.732	6.141
	3	1.572	-1.596	1.636	5.372	-12.942	9.157
	4	1.461	-1.460	1.364	10.670	-19.347	13.657

Table 2. Induced stresses at cancellous, cortical bones for different implant lengths, and bone qualities for screw type implant.

Implant length (mm)	Bone quality	Cancellous bone stresses (MPa)			Cortical bone stresses (MPa)		
		Tensile	Compressive	EQV	Tensile	Compressive	EQV
9	1	1.479	-3.689	2.707	1.983	-8.781	6.334
	2	1.481	-2.935	2.666	2.232	-9.690	6.955
	3	2.180	-2.117	2.384	7.245	-16.023	11.273
	4	1.981	-1.673	1.896	14.479	-23.576	16.831
10	1	1.358	-4.115	2.387	0.965	-8.752	6.365
	2	1.347	-3.421	2.332	2.209	-9.069	6.944
	3	1.925	-1.879	2.196	7.125	-14.641	10.844
	4	1.783	-1.474	1.740	13.489	-21.466	15.977
12	1	1.077	-4.266	1.943	1.785	-8.030	5.931
	2	1.114	-3.517	1.964	2.023	-8.787	6.422
	3	1.658	-1.662	1.871	5.798	-13.109	10.277
	4	1.410	-1.408	1.524	11.563	-19.721	15.274
14	1	0.964	-4.137	1.901	1.802	-8.277	6.026
	2	1.021	-3.363	1.596	2.039	-8.917	6.481
	3	1.561	-1.502	1.705	5.263	-13.124	9.022
	4	1.491	-1.386	1.457	10.340	-19.765	13.320

Table 3. Induced strains at cancellous, and cortical bones for different implant lengths, and bone qualities for cylinder type implant.

Implant length (mm)	Bone quality	Strain at cancellous bone (10^{-3})			Strain at cortical bone (10^{-3})		
		Tensile	Compressive	EQV	Tensile	Compressive	EQV
9	1	0.192	-0.278	0.292	0.130	-0.525	0.436
	2	0.287	-0.404	0.431	0.143	-0.594	0.489
	3	1.095	-1.382	1.543	0.566	-1.096	0.911
	4	1.954	-2.048	2.716	1.107	-1.559	1.296
10	1	0.177	-0.248	0.266	0.126	-0.579	0.484
	2	0.267	-0.365	0.397	0.144	-0.638	0.533
	3	1.035	-1.296	1.463	0.535	-0.958	0.830
	4	1.871	-2.300	2.613	1.443	1.036	1.249
12	1	0.148	-0.207	0.219	0.125	-0.553	0.464
	2	0.225	-0.308	0.333	0.140	-0.602	0.505
	3	0.911	-1.252	1.426	0.475	-0.966	0.808
	4	1.694	-2.310	2.635	0.932	-1.328	1.109
14	1	0.119	-0.163	0.175	0.118	-0.507	0.436
	2	0.183	-0.248	0.269	0.133	-0.549	0.472
	3	0.784	-0.926	1.022	0.444	-0.851	0.704
	4	1.520	-1.790	1.974	0.904	-1.275	1.050

Table 4. Induced strains at cancellous, and cortical bones for different implant lengths, and bone qualities for screw type implant

Implant length (mm)	Bone quality	Strain at cancellous bone (10^{-3})			Strain at cortical bone (10^{-3})		
		Tensile	Compressive	EQV	Tensile	Compressive	EQV
9	1	0.196	-0.262	0.285	0.129	-0.580	0.487
	2	0.283	-0.355	0.410	0.144	-0.638	0.535
	3	1.006	-1.268	1.490	0.540	-1.018	0.867
	4	1.851	-2.294	2.748	1.056	-1.519	1.294
10	1	0.173	-0.214	0.251	0.127	-0.589	0.489
	2	0.250	-0.317	0.358	0.142	-0.644	0.534
	3	0.981	-1.115	1.372	0.499	-0.963	0.834
	4	1.825	-2.077	2.522	0.991	-1.433	1.230
12	1	0.136	-0.214	0.204	0.112	-0.538	0.456
	2	0.200	-0.262	0.302	0.127	-0.583	0.494
	3	0.862	-0.986	1.169	0.443	-0.941	0.790
	4	1.641	-1.931	2.209	0.893	-1.400	1.174
14	1	0.131	-0.210	0.200	0.123	-0.557	0.463
	2	0.177	-0.235	0.245	0.138	-0.600	0.498
	3	0.754	-0.857	1.065	0.412	-0.828	0.694
	4	1.704	-1.726	2.112	0.829	-1.228	1.024

4. Discussion

In this study, two different designs of implant, four bone qualities, and four different lengths were analysed. The biomechanics of the dental implants have been studied by many researchers and these studies are based on several parameters such as influence of thread geometry, bone quality, and implant design for titanium as implant material (27-29).The reports from the clinical observation showthat the failure of the implant happens due to considerable bone loss around the neck of the implant. Furthermore, it is evident from experimental (10, 24), and clinical studies (3, 5, 7-9) that the failure of the implant occurred because of bone loss as well as adverse loadingsituations. Improper loading leads to bone resorption due to excessive stresses developed in the bone and implant. Hence, it is important to study the stresses/strains with respect to various parameters. Moreover, it is difficult to examine biomechanical responses through experimental, and clinical attempts with restricted information. . Hence, the current study aimed to examine the influence of a zirconia implant on different bone qualities, different types of length, and different shapes using the three dimensional linear finite element analysis, which has been a commonlyrecognized tool for biomechanical investigation. The outcome of this analysis compared with the existing results obtained from titanium as an implant material.

The contact between the implant-bone interfaces plays a vital role to determine the biomechanical responses. The attempt made by many researchers to determine the biomechanical factors assumed bonded, and slip contact between the bone-implant interfaces. The observations from previous FEA work (30, 31) showconsiderably notable variations in induced stresses and strain values between the bonded and slip contact. Also, the experimental evaluation was found to be limited in order to determine the most valuable contact (30). But, the removal torque method shows that implants with a roughed surface often resulted in fracture than a machined surface in the bone (32) suggesting that the contact between the bone and implant was bonded. Therefore with respect to the above observations the bonded contact was used between the implant and bone interface for roughed surface implant, as used in this study. The implant failure frequently occurs in shorter implants and it is hardly found in longer implants (33).In addition to this, it was not identified where the failure will occur. It may occur in the implant alone or the bone around the implant. Hence, the current study examined the implant and bone stresses as well and the results were compared on the basis of the longer versus shorter.Screw, and cylinder type implants are generally used in dentistry and induced stresses/strains are compared in the current analysis. Implants positioned in type I, II bone display good correlation;, however, the rate of failure is found to be more in type IV bone (8, 18).The failure of the implant intensely depends on the density of the cancellous bone, and the elastic, strength properties very much depend on the porosity of tissue (34). Hence, the different elastic moduli have been used to represent the bone qualities and also to evaluate the effect of stresses and strains on the bone and implant. The bone quality is also differentiated by variations in the cortical bone thickness, and cancellous bone architecture, which is not included in this study.

The stresses induced in various bone qualities are extensively affected by the assigned material (35, 36).The effectiveness of titanium dental implants was analysed in many studies (35, 37), while only a few studies focused on the zirconia dental implants (38, 39). Moreover, no one studied the influence of the implant type, length, and bone quality on stress distribution, using zirconia as a material. The investigation of the current study shows that stresses in the cortical bone are not affected much by the type of implant, and bone quality, and these findings have good agreement with the existing FEA (37) study performed with a titanium dental implant. The ability to withstand more load is found in the cortical bone than in the cancellous bone because of variations in the elastic modulus (17, 40). Furthermore, cortical bone becomes stronger due to high elastic modulus and has a good resistance against deformation. The output from the current study marked more stresses in type III, IV bone and smaller stresses in type II, I bone and is in good accordance with previous studies. (37,41). The important observation found in this study is that zirconia dental implants induced lesser stresses in type III, IV bone, and slight increment in stresses in type II, I bone compared to titanium. This needs to be investigated further.

The decrease in the elastic modulus of cancellous bone leads to a reduction in the strain level for both cylinder, and screw type implants. This result has good agreement with another study (37), but the important observation found is that, regardless of the implant type and bone quality, the zirconia dental implant induced lesser stains than the titanium dental implant.Additionally, the EQV strain in the cancellous, cortical region is found to be increased in each bone quality, for all lengths of the implant, and types III, and IV bone induced the maximum EQV strain. But the 9 mm length, cylinder type implant produced the maximum strain at type III bone, and the screw type implant induced the maximum strain at type IV bone. The Maximum EQV strain was observed in type II, III bone for 10 mm, 12 mm lengths of cylinder type, while type IV bone causes maximum strain for 14mm length. The result of this study differs from that of the previous study of a titanium dental implant; hence, this should be considered to investigate further.

The maximum amount of failure rate has been found in type IV bone according to the clinical reports (8, 18).Because it is a low density bone, the stiffness of this type of bone is less, and produces significant displacement in the implant. The result of displacement induces maximum deformation; thus, the maximum stresses and strains are observed in cancellous, cortical bone. This resultconcurs with that of the present study and the maximum EQV stresses were detected in type IV bone rather than types I to III.

The implant successis also influenced by another important factor called implant length. The failure rate of the 7mm long implant was found as10.7%, while it was 5.9 % for the implant length of 10mm, and 13mm and no failure was observed for the implant length of 15mm, according to the study. (8).However, the length of the implant is not taken into account for good quality bone. In this analysis also, the implant length generated the maximum EQV stresses in type III, IV bone and this is in good accordance with the previous studies, suggesting implant length and bone quality asaspects that impact implant success.

The observation of the current study indicates that decrease in bone density leads to the maximum implant stresses. The fracture of the implant is hardly found in clinical reports. (2, 15, 41, 42) and the outcomes of the current study have matched those reports which show that the screw type implant produces more stress than the cylindric type;, thus, screw type implant leads to more risk.

The stress/ strain distributions in two types of implants, namely, screw, and cylindric were analysed and the results were compared in this work. Similar to other FEA studies where titanium was used as the dental implant, no significant variation was found among screw, and cylinder types for zirconia dental implants when positioned in type I, II bone which have been represented as high density bones. For types III, and IV bone, screw type implant bone may be suggested.

5. Conclusion

The biomechanical mechanism of a zirconia dental implant was studied for different bone qualities, different implant lengths, and different types of implant. The zirconia dental implant provides significantly more benefits than titanium implants; still, more investigation is required for its clinical usage. The following inferences can be drawn from this study.

The stresses in the bone can be reduced using zirconia as a dental implant material.
Regardless of the implant type, and EQV strain, the EQV stress at the cancellous, cortical bone region increased for low density cancellous bone. Hence, the significance of the bone quality has been confirmed. The screw type implant of titanium induces EQV strain at the cancellous region lower than the cylinder type dental implant, but the magnitude of strain has been found less in the zirconia dental implant for low density bone. Hence, the zirconia screw type dental implant may be a good choice in a jaw where the cancellous bones have low density.

In a similar manner, longer implants generated lower stresses than shorter implants in the low bone density region. Therefore, longer implants are suited for low density bone. Only axial load was considered in this study. The effect of lateral load on bone quality, implant type and length may be recommended for future work.

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