Hindawi
Shock and Vibration
Volume 2022, Article ID 1667838, 9 pages
https://doi.org/10.1155/2022/1667838

Research Article

Structural Evaluation of the Effect of Bone Quality on the Mechanical Interaction between Dental Implants and Bone

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Received 6 June 2022; Revised 6 July 2022; Accepted 18 July 2022; Published 31 August 2022

Academic Editor: S. S. Mahdi Kolbadi

When one or more teeth are lost for any reason such as accident, caries, and gum disease, they should be replaced with dentures. Researchers discovered that titanium successfully bonds to bone because of the development of osteoblasts on its rough surface. However, the success of dental implants depends on biological, mechanical, and chemical factors. Each of these factors is itself a function of different parameters that, any changes in these factors affect the mechanism of transfering from the prosthesis to the implant and from implant to bone. The role determinant in the success of implant therapy is the function of the geometry and mechanical properties of the implant, jaw and bone-implant joint. Now, due to the increasing use of dental implants, various companies are constantly launching their new products and, as a result, express many benefits of these products, which in most cases are based on their claims. It is not a long-term study, and therefore it is not possible to make an accurate judgment on the designs, macroscopic and microscopic properties, and benefits offered, due to the lack of accurate and practical comparisons between systems. It will not be possible to prove the effectiveness of each of them. Therefore, understanding the design method and its philosophy, along with familiarity with the types of systems available in the market, is a determining factor in the clinical success of dental implant treatment. The presence of threads prevents overload on the surface of the cortical bone and reduces this load by up to 36%. Reducing the thread pitch contributes to the stability of the implant, and increasing the depth of the thread stabilizes patients with poor bone quality. The behavior of the bone and its relation to the implant with regard to applied loads with a maximum inclination angle of 15° have been evaluated by evaluating the tension in the bony areas of the cortex and trabecular bone.

1. Introduction

Dental implants are a good alternative to dentures because of their many advantages over other types of dentures, including providing sufficient stability and adhesion, preventing bone resorption, and eliminating the need to shorten abutments. Today, most studies on dental implants are based on the development of integrated implants, which were first proposed by Branemark. They are located in the jawbone and play the role of the root of the missing tooth. However, the use of dental implants has never been without problems [1, 2]. Loss of one or more teeth is a problem that is difficult and even unbearable for many people. But for various reasons, you may encounter such a complication. Until recently, there was no choice but to use dentures [1, 3]. Clinically, some of the most important reasons of implant damage are unsuitable bone graft [4], complications with surrounding soft tissue [4], biomechanical problems [2] , poor quality of maxillary bone (Sun et al., 2014), axial loading of implants [4], and unhealthy habits related to teeth such as gnashing teeth [3]. Both M12 and Astra Tech implants show a good distribution of forces for compressive and oblique loads without concentrating the force in a specific area of the bone/implant interface [6].

Bone integrity, as the key to the success of implant treatment, was defined on the basis of direct contact of parts of the implant surface and bone under light microscope magnification (Markian et al., 2018). According to his studies, titanium was finally introduced as a highly compatible material in the process of bone integration. Due to the successful results of titanium, it is still used as the main material in the manufacture of dental implants [7]. A key factor in the success or failure of dental implants is the optimal distribution of stress in tissues and bones. It has been reported that dental implants are influenced by many factors, including implant design, bone size and quality, surgical procedure, postoperative care, implant length and diameter, and implant location. For example, among these factors, we can mention threads. Threads are used in dental implants to maximize initial contact, improve initial stability, and help reduce surface tension. Moreover, the depth of the thread, the thickness of the thread, the shape of the thread, the number of threads, the angle of the face of the thread, and the helical angle of the thread are different geometric designs that characterize the performance of the thread. In addition to the above, the thread step has an important clinical role and importance in the protection of dental implants under axial and non-axial forces. Another example is the length of implants. Since finite element analysis has a high capability of modeling and analyzing such issues, it can be a very good method for thermal analysis of implants and calculating the stress of different parts of all components, especially bone. Another advantage of the finite element method is the lack of laboratory limitations in examining the effect of different parameters on the temperature of the implant and bone components. In addition, it can obtain a very good schematic view of the distribution and temperature gradient in the whole set, which has been studied in the present study.

2. Literature Review

Going back several thousand years in the history of dental implant replacement, which is related to several historical regions and periods, and referring to the more recent history of implant dentistry, we can mention Maggiolo, which is made of gold as a root. It was used as an implant in 1809. The first root-shaped design which was markedly different from the previous works was the iridium-platinum lattice cylinders in 1909. Reports indicate that the implant has had little success [27]. As a turning point in the process of implant research, we can mention Branemark, who has done a lot of studies in the field of implants. A series of his studies began in 1952, which led to the use of new implants in the early 1960s (Amiri, 1398). His implant studies were first performed on dogs, then his human studies began in 1965, and the 10-year practical results of these studies were reported in 1977 [8].

Advances in dental implant medicine and the increasing desire of patients and doctors to use it have caused the significant growth of this method [27]. One of the aspects discussed in the field of dental implants is how the biological response in the treatment process. For this purpose, at present, in order to better realize this method of treatment, which is more successful and safer than other proposed methods, a lot of research has been done to improve and predict different implant responses to different factors and parameters. Those involved should be carefully evaluated [2]. Therefore, one of the necessities and needs of treatment methods for toothless types is their aesthetic discussion, which has been accepted in the case of implants [9]. On the other hand, apart from the discussion of beauty, one of the main tasks of dental implants is to establish the function and tolerance of the forces on the system, so familiarity with the principles of biomechanics will make the treatment plan safer and have a predictable future. Therefore, one of the most important aspects of biomechanical knowledge is to know the type of loads and how they are applied and to know the response of biological tissues to the loads. In this regard, protocols on how to apply the forces and loads have been introduced [10].

However, the presence of a risk factor cannot be an obstacle to implant treatment, but if several indicators are found in the disease at the same time, the risk of treatment failure should be considered. However, biological and biomechanical factors should be considered some time before implant replacement [11]. Clearly, in the cycle of reviewing and producing implants, biomechanical factors have been considered by researchers for many years; therefore, in the following, the effective factors related to the biological and biomechanical conditions of implants, which have contributed to the failure or success of implant treatment, are reviewed by reviewing previous research [27]. The destruction mechanisms of bone stew integration in implants are similar to natural teeth; however, due to the lack of periodontal fibers around the implant tissue, excessive biomechanical pressure, after restoration, can lead to failure of implant treatment. In this case, the factor of premature bone resorption can aggravate the condition, so that the lack of complete bone integrity of the implant, considering the lack of periodontal fibers, will cause tissue damage and consequently failure of treatment [7].

In addition to how loads are applied and transferred, the nature and extent of their application are also considered as important criteria in the success of treatment in the process of bone-implant integration. In this regard, in order to form and renew bone in the injured area, there must be a minimum load on the implant to strengthen the bone. From another point of view, it should be borne in mind that by increasing the ratio of the length of the crown to the body of the implant, it is possible for more lever forces to enter the bone, especially in lateral movements. Therefore, in this case, more implants should be used or the number of cantilever crowns should be minimized. Having parafunctional habits such as bruxism and anthrax, which cause continuous lateral loads to be applied to the bone during bone repair, causes serious damage to the bone integration process and disrupts implant treatment [12]. The implants biomechanics and effective biological factors in their treatment process is discussed in some research [13]. Firstly, a brief introduction is given about incisor tooth and various factors of its defect. Then, different treatment plans to eliminate the deficiency of natural teeth, in general, are discussed, and then the treatment plans used for the second tooth will be stated [7]. One of the recommended principles for the success of implant

Table 1: Time intervals between tooth extraction and implant placement [10].

Group	Method	Advantage	Disadvantage
1	Implant placement right after tooth extraction in the same session	Reducing the overall steps and time of treatment. Maximum bone volume availability and reduced risk of bone resorption. Shortening of the edentulous period. More rapid bone integrity at the site of tissue repair	The socket shape of the teeth may interfere with implant placement in the ideal position. The thickness of the gums makes it difficult to achieve the desired results. Lack of adequate keratinized mucus makes flap adaptation difficult. It requires sufficient experience and needs a bone graft to remove possible bone damage
2	Implant placement after complete soft tissue restoration on the dental sac 4-8 weeks after tooth extraction	Increasing the volume and width of the soft tissue, in order to control the flap. Removal, pathological lesions (4-8 weeks after tooth socket extraction)	Changes from hard tissue analysis may jeopardize implant placement in the ideal position. The treatment time is long. The socket walls of the tooth undergo different analyses. There is a need to increase bone volume
3	Implant placement after complete soft tissue restoration on the dental sac 4-8 weeks after tooth extraction	Relatively easier in socket tooth filling. Easier control, flap with soft tissue maturation	Longer treatment time bone resorption has occurred in some of the socket walls. There is a need for inadequate bone reconstruction
4	Implant placement after complete restoration (after 16 weeks of tooth extraction)	We are facing a restored ridge. The soft tissue has matured	The treatment time is very long. There is a need to rebuild lost bone. The amount of bone available is highly variable and unpredictable

treatments, according to the theory, is a 12-month waiting period between the time of tooth extraction and implant placement. The logic of this work is to eliminate the pathological lesions of hard and soft tissues that have led to tooth extraction [14]. But it should be noted that during the first 4 months after tooth extraction, the width of the Bucklingo Ridge will be reduced by 5–7 mm and its height by 2–4.5 mm. This becomes more acute when the number of extracted teeth is higher. Under these conditions, the rate of bone height analysis will be higher [15].

Most of these changes, which last up to 12 months, occur in the first 3 months after the teeth are extracted. For this reason, researchers have tried to devise a new method so that the implant can be placed in a toothless place immediately after tooth extraction. The first attempt at immediate implant placement began in 1976 with the use of polycrystalline aluminum implants [16]. Given these issues and considering that the most important factor in determining the time interval between the implant placement and the initial load applied to it is bone quality, the softer the bone and the lower the quality, the longer the post-implant repair period. It is worth noting that after the teeth are extracted, the bone decays in width and then in height. In the first year after tooth extraction, the width of the bone is reduced by 25% and its height is reduced by 4 mm [17]. If there is not much time between the extraction of the teeth and the start of treatment, it is possible for the desired volume of bone to remain. In this situation, due to bone width of more than 5 mm, height of more than 12 mm, and mesiodistal length of 7 mm or more, it will be possible to place a standard implant [18]. However, in ideal conditions, the height of the anterior bone in the upper and lower jaw with the appropriate bone material, of the first or second type, in addition to providing standard implants, also allows the implantation of long-base implants.

During the first week after tooth extraction, cell proliferation begins to increase the volume of connective tissue, and then the opening of the cavity is covered with keratinized epithelial mucosa. Under these conditions, the resorption of the lower bone and the adaptation of the upper mucosa to the new shape of the bone make the hard and soft tissue available for implant placement less compared to natural teeth. Prolonged absence of teeth and lack of stimulation of ossification lead to the complete disappearance of alveolar growths. And the analysis will follow to the level of the basal bone, in which case the changes are made, and the maxilla is completely flat. The corset and its posterior areas add to the problem by merging the horny and myeloid muscles; eventually, this causes the final crown to reach a height of more than 20 mm, which is another factor in increasing the pressure and forces (Table 1). It will be a lever on the prosthesis [16]. In case of bone resorption in the maxilla, the presence of a sinus will be an important factor in limiting the height. The height of the lower jaw is similar to that of bone resorption, an alternative method of treating the weakened area, bypassing the mandibular nerve, and considering a chin hole to the possibility of its defects. The protrusion of the nerve is through the chin hole, in order to allow the placement of tall implants, but in the case of nerve lifting, there are possible risks, such as permanent nerve damage can be avoided [19]. Adequate*t* during operation may have occurred. Another method used in the mandible, which can be used in the early stages of bone resorption without lifting, is bone marrow transplantation, which allows the implant to be implanted without the risk of nerve displacement [20].

3. Research Background

In 2017, [21] conducted a study entitled "The Effect of Optimal Orientation on Dental Implants and Its Impact on the Bone Quality of Implants under Frequent Mechanical Loading" [22]. The aim was to investigate the effect of groove designs on bone quality under repetitive load conditions to optimize dental implant design. Anodized Ti-6Al-4V alloy implants with negative 60 and positive 60 degree grooves around the neck were placed in the proximal tibial metaphysis of rabbits. Repeated mechanical loading through implants (50 N, 3 Hz, 1800 cycles, 2 days per week) was started 12 weeks after surgery for 8 weeks. Bone quality, defined as osteocyte density and degree of biological apatite (BAp) axis c/collagen fibers, was then evaluated. Groove designs without mechanical loading do not affect bone quality. However, repeated mechanical loading significantly increased bone contact with implants, bone mass, and bone mineral density (BMD). In +60° grooves, the c/collagen BAp axis fibers are preferably aligned along the groove direction by mechanical loading. In addition, osteocyte densities were significantly higher both inside and next to the +60° grooves, but not −60° grooves. These results show that +60° grooves successfully transferred the load to the bone tissues around the implants through the grooves. A groove structure with optimal orientation on the implant surface was shown to be a promising way to achieve appropriate bone quality. This is the first report to provide the optimal design of grooves on the neck of dental implants to improve bone quality parameters as well as BMD. Findings show that not only BMD but also bone quality can be a useful clinical parameter in implant dentistry [23]. However, most of the previous researches in performance improvement field of geometric structure optimization, such as the implant appearance, the surface polishing threads condition, adding materials, and implementing methods. However, few studies have comprehensively examined the various parameters and presented the results in a comparative manner.

According to Linetskiy et al. (2017) [24], for dental implants to be successful, experimentally set thresholds must limit bone stress. From these criteria, the final functional load, which determines the load carrying capacity of the implant, can be calculated. Obviously, reducing it due to bone loss shortens the life of the implant. A comparison of how bone loss affects the final functional loads of different implants can provide significant feedback to the physician on the suitability and longevity of implants. The aim of this study was to evaluate the lifespan of different dental implants placed in I-IV bone types based on the comparison of their final functional loads taking into account the bone loss factor [25]. Von Mises stress and the first major strain distribution at the bone-implant joint surface were studied, and the final functional loads were calculated. Models of I-IV bone types were designed. Implants of 3.3 × 8.0 mm (A), 4.1 × 12.0 mm (B), and 4.8 × 14.0 mm (C) were analyzed at 10 levels of bone loss. The final functional loads, which exert the final von Mises stress and the first major pressure on the bone, were calculated. For implants A, B, and C placed in type I bone, the final functional load values were higher than 120.92 Nm of experimental functional load, corresponding to +10 years of service with an annual bone loss of 0.2 mm. For the second type of bone, the lifespan was 4 and +10 years. For type III bone, the lifespan was 4 and 5 years. For type IV bone, the first major strains were initially harmful to all implants. In oral implantology, bone loss is an essential factor in predicting implant longevity [26]. When assessing the load capacity of the implant, physicians should consider the factor that reduces the life of the implant.

According to da Cunha et al. (2015) [27], the mechanical entanglement between a mini-implant (MI) and the bone substrate directly reflects the initial stability achieved. The aim of this study was to evaluate the design performance of MI in distinct bone substrates and the relationship between geometric features and insert quality. Two types of self-drilling MIs (1.6 × 8 mm) were assigned to two groups according to their geometric designs: Tomas system (Dentaurum, Ispringen, Germany) and Dual-Top (Rocky Mountain Orthodontics, Denver, Colo). 40 slices (8.10 mm) were taken from bovine pelvic ilium and pubic bone. Geometric design features were evaluated using scanning electron microscopy and Image-Pro Insight software (Media Cybernetics, Rockville, MD). Bone quality parameters were evaluated with a microcomputer tomography system, and initial stability was assessed with insertion torque and extraction power. Intergroup comparison was performed with analysis of variance, Tukey tests, and Pearson correlation test ($P < 0.05$). No significant differences were observed between the groups in ilium (Tomas: insertion torque, 12.87 Nm; pull-out power, 181 Nm. Dual-Top: insertion torque, 9.95 Nm; pull-out power, 172.5 Nm). However, Tomas group had a significant increase in insertion torque (25.08 N • cm; $P < 0.05$) in pubic bone. The mechanical performance of MI varies according to bone quality parameters, which indicates that certain geometric parameters may be adjusted depending on the insertion medium [28].

4. Materials and Methods

In this research, the strength of two ordinary dental implants that were exposed to the chewing load of 400 N was reported for different *f* bone quality. The present study is descriptive-analytical and is applied in terms of purpose [29]. Therefore, in this study, we try to analyze the finite element of the effect of bone quality on the mechanical interaction between the implant and the bone. In order to achieve the goals in this research, we deal with finite element simulation. First, the screw design is done in three dimensions [30]. In the following, the materials of each part are identified, and the research model is simulated by determining the boundary conditions and properties of the materials. We use two implants with a diameter of 4 mm and a length of 13 mm which increase the level of contact with the bone (Figure 1). Model 1 (M12) has a neck length of 3 mm and Astra Tech 4013 implant with a double inner hexagon and a surface that is blown (Figure 1). The main reason for studying these two implants is evaluating the effect of threads shape on the response load [31].

5. Types of Bones

Misch proposed bone classification based on the density and thickness of the cerebral cortex as presented in Table 2. Table 3 also illustrates the density and thickness of the cortical region.

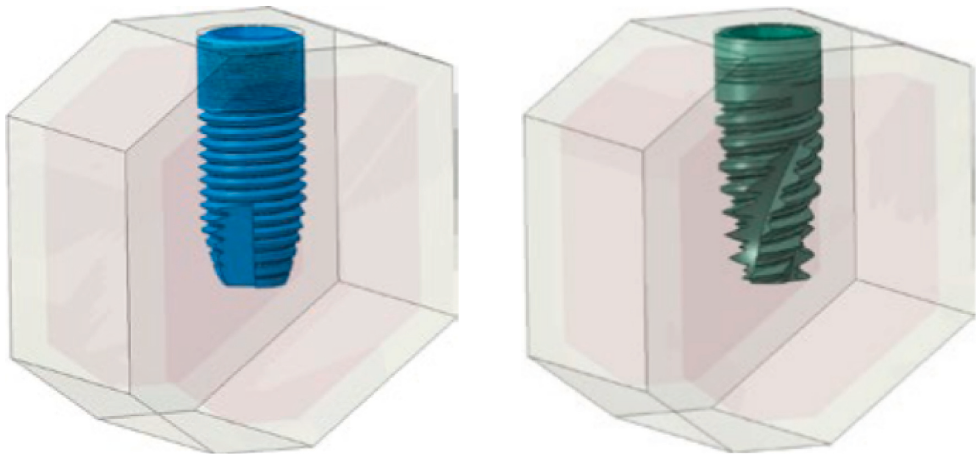

Figure 1: Model overview for M12 and Astra Tech implants.

Table 2: Classification of bone density [32].

Bone density	Description	Anatomical position
D1	Dense cortex	Anterior mandibular region
D2	Porous cortex and thick trabecular bone	Anterior mandibular region Posterior area of the mandible Anterior maxillary region
D3	Porous cortex and thin trabecular bone	Anterior maxillary region Posterior area of the maxilla Posterior area of the mandible
D4	Thin trabecular bone	Posterior area of the maxilla

Table 3: General properties of the bones [33].

	Cortical bone			Trabecular bone	
Bone type	Thickness (mm)	Young modulus (GPA)	Poisson's ratio	Young modulus (GPA)	Poisson's ratio
D1	2.5	13.7	0.3	9.5	0.3
D2	2.0			5.5	
D3	1.5			1.6	
D4	1.0			0.7	

6. Finite Element Model

The two materials are meshed using C3D4 elements, first-order quadrilaterals mesh. In this method, similar to the method of linear static analysis, the response of the structure in the earthquake is multiplied by the desired level of risk in coefficients to match the maximum deformation of the structure with what is predicted in the earthquake. For this reason, the internal forces in malleable structures that will behave nonlinearly during an earthquake are estimated to be greater than the tolerable forces in the structure. Therefore, when examining the acceptance criteria, the results of linear analysis are corrected for structures that behave nonlinearly during an earthquake. The number of vibration modes in spectral analysis should be chosen so that the sum of the effective mass participation rates for each extension of the earthquake excitation in the selected modes is at least 90%. In each stretch, at least the first three oscillation modes must be considered and at least all modes with a rotation time of more than 0.04 seconds. The design range used in this method should be selected in accordance with the regulations. The results of each oscillation mode should be obtained with known statistical methods such as SRSS (square root of the sum of the squares), full squared combination method (CQC), or methods that consider the interaction between modes more accurately. The effect of an earthquake perpendicular to the desired length should be considered if necessary (Shang et al., 2017). In time history analysis, the response of the structure is calculated using dynamic relationships in short time steps. In this method, the response of the structure under the excitation of the ground acceleration should be calculated based on at least three acceleration maps. If less than seven accelerometers are selected for analysis, their maximum effect should be considered to control deformations and internal forces [34]. If seven or more accelerometers are used, the average value of their effect can be considered to control deformation and internal forces.

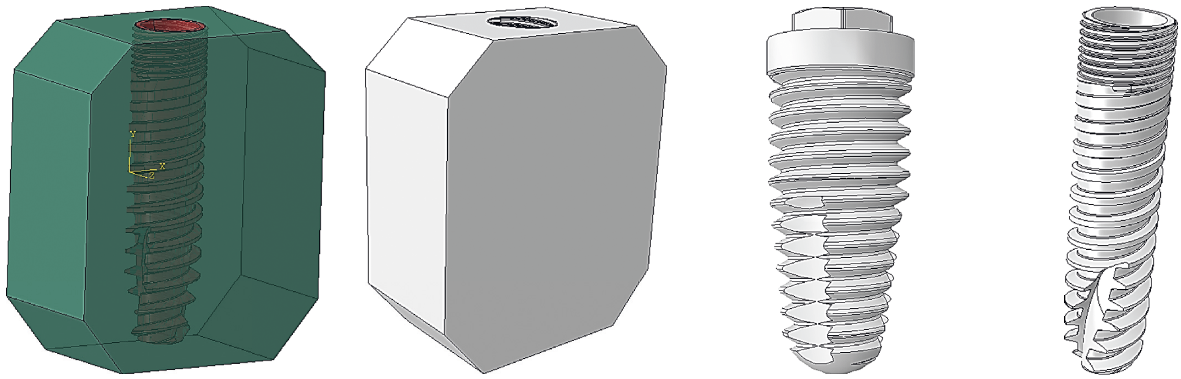

Figure 2: Screw M12, Astra Tech, and bone in software and assembly of both models in simulation.

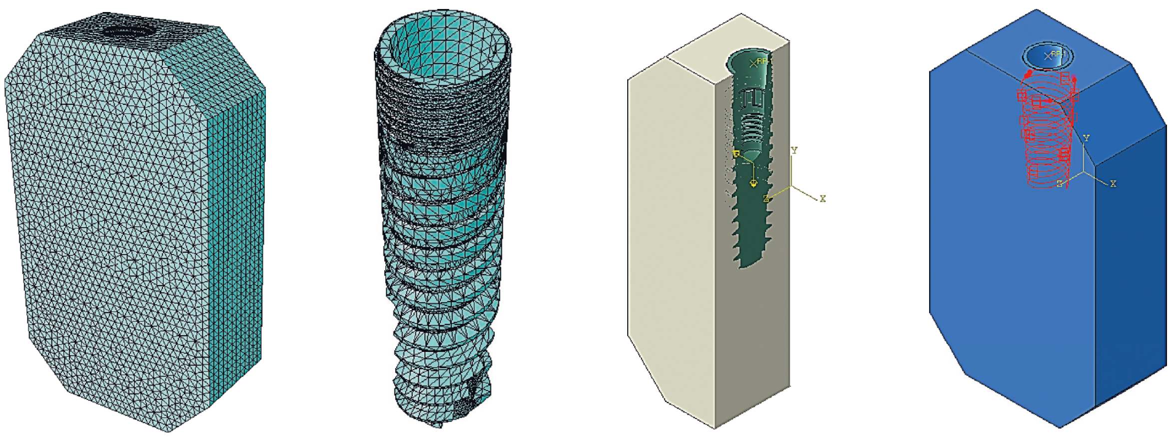

Figure 3: Areas of contact between the two models, force on the screw, implant screw grid, and bone grid.

7. Problem Analysis and Research Findings

Analysis of the results obtained from the data collection stage is one of the most important parts of any research, because of extensive research in theoretical studies, background research, data collection, and field treatment. It is a collection of tested information that reveals to researchers how valid and accurate the assumptions made by their studies are. Therefore, it is necessary to analyze the obtained data with accurate and scientific methods and with great accuracy and sensitivity so that their generalizability is possible with high reliability. In this regard, creep investigation in composite car tanks under pressure is performed by Abacus software. At the beginning of the problem solving, the simulation model is drawn in the part module. According to the geometry of the appropriate dimensions and sizes, the problem is entered. Figure 2 shows the models created in Abacus. The created models are divided into 2 parts, one is the implant screw and the other is the bone inside which the screw is located.

In the assembly module, problem models are entered and positioned relative to each other. Figure 3 shows the assembly of both models. In the interaction module, contact is defined between the two models of implant screw and bone. Figure 3 shows the contact model between the two models and the contact characteristics. The contact areas are also shown in Figure 3.

In the initial time step, the plates around the bone are completely fixed in the longitudinal direction (z), and the lower plate is stationary in all directions, but the upper plates are not considered fixed. Figure 3 shows the defined supports for the bone. Next, for the screw, a force of 400 N is defined at an angle of 15 degrees in the y direction. Figure 3 shows the definition of this force on the model reference point. In this case, the type of network in the polymer model is Tet. Moreover, the implant screw model is Tet and triangular. According to the mentioned methods, networking is done in an organized way. Furthermore, the type of element used in the screw is C3D4, and the number of meshes is 141136. The size of the networks is chosen in such a way that proper analysis is performed. Figure 3 shows its geometry and networking. The bone model is then networked triangularly and with the C3D4 element type. The number of bone marrows is 149,000. Figure 3 shows bone mesh.

8. Numerical Results

The purpose of this finite element analysis is to evaluate the effect of bone quality on the mechanical interaction between dental implants and bone. By solving the problem, it is possible to view the results in the visualization module. After analyzing the four bone configurations for the two proposed load conditions, the maximum stress values were obtained in the cortical bone region and in the trabecular bone region.

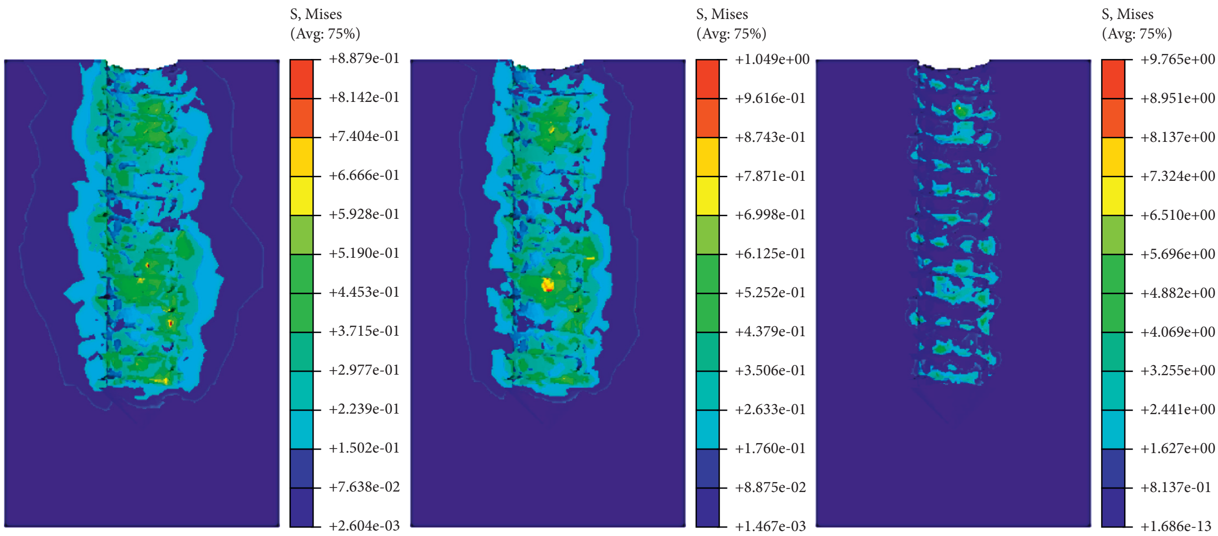

Figure 4: Contour of stresses on the bone in 0.07, 0.88, and 1 seconds.

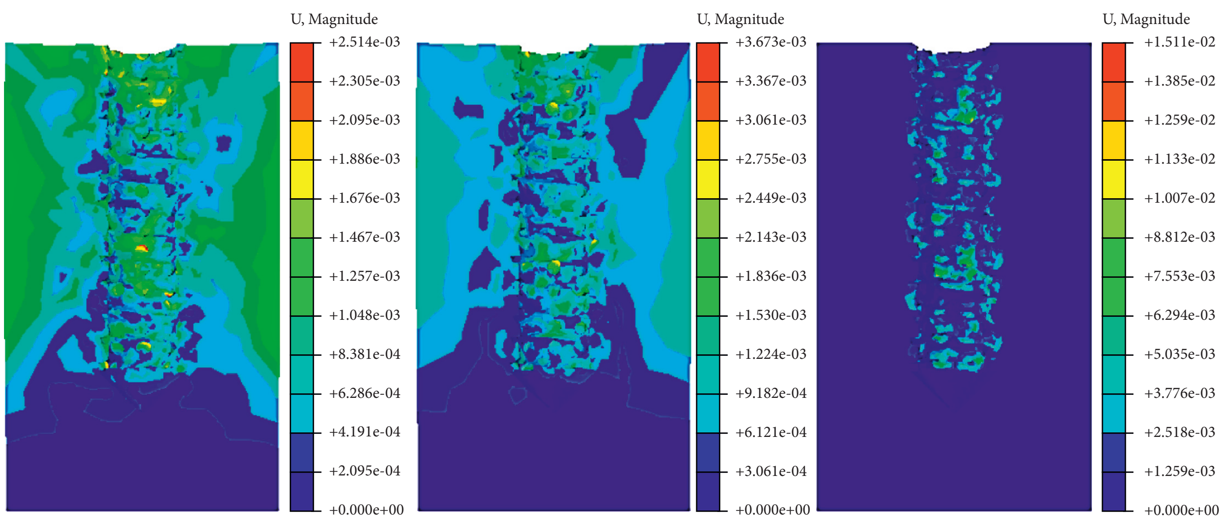

Figure 5: Bone displacement in 0.076, 0.88, and 1 seconds.

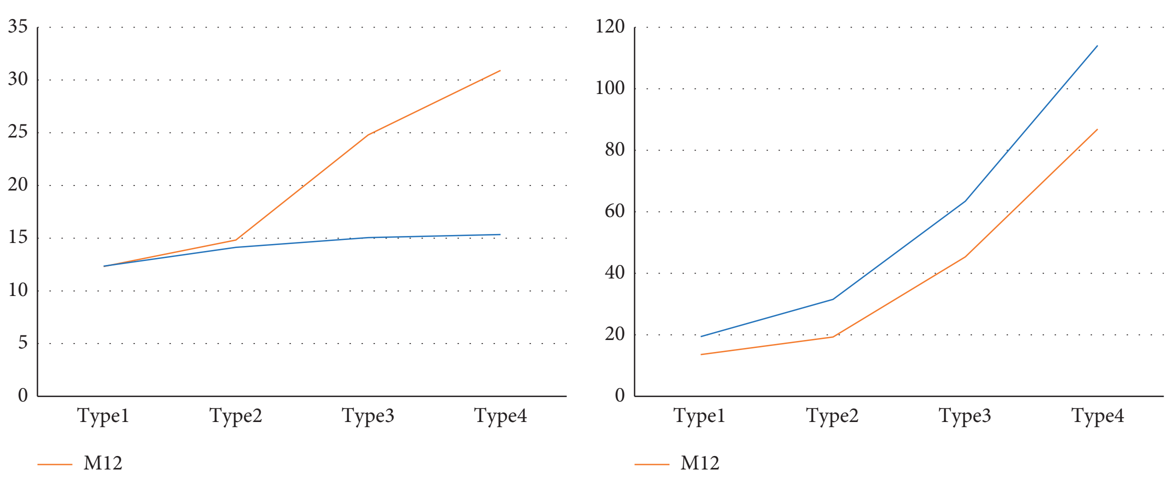

Figure 6: Maximum tension in the cortical and trabecular bone for the compressive load depending on the type of bone.

Figure 4 shows the stresses applied to the problem during the simulation process in the first type of bone.

The stress distribution is well displayed in the created cross section. The greatest amount of stress is applied to the parts of the bone that are sunk into the screw. This maximum value is 888 MPa. The amount of stress in the parts of the bone involved in the implant screw varies from 224 MPa to 888 MPa. It is observed that the more time passes after the analysis, the more stress distribution is observed in the model. To analyze the amount of bone displacement due to pressure applied to the screw, the amount of bone displacement contour is displayed. Figure 5 shows the displacement created in the bone in different seconds of the simulation.

It is observed that the greatest amount of displacement is observed in the parts of the bone that are sunk into the screw. This maximum value is equal to 2.51 micrometers. In addition, the most displacement is observed in the parts of the bone that are involved in the screw. Moreover, with increasing simulation time, the number of points involved in displacement in the model has increased. Due to the compressive load, as shown in Figure 6, implants showed more tension in the cortical bone region than in the trabecular bone region.

9. Conclusion

The aim of this study was to use numerical simulation techniques based on finite element method to evaluate the influence of the bone quality on the mechanical interaction between the implant and the bone and on the stresses caused by the two implants under compressive and oblique loads. In both cases, the load distribution may be consistent with the maxillary bone resistance and similar moderate-pressure stimuli. Decreased bone quality has a negative effect on the stress caused by implants, mainly in the bone marrow area. Numerical modeling is performed by considering bone as a linear isotropic material. This concept has a direct application to the cortical bone due to the low porosity and elastic behavior of the bone at the macroscopic level for the assessed load condition. The use of this material model for trabecular bone depends on the definition of the Young module, which sufficiently demonstrates the macroscopic behavior of the trabecular bone by considering the percentage of porosity and the dimensions of the cavities that represent the bone.

Data Availability

Requests for access to data should be made to the corresponding author, e-mail address: nazanin.karami@srbiau.ac.ir.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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