Comparative finite element study of the influence of implant design, inclination, load direction and maxilla bone composition on stress and strain distribution

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RESUMEN

TÍTULO: ESTUDIO COMPARATIVO DE LA INFLUENCIA DEL DISEÑO E INCLINACIÓN DEL IMPLANTE, DIRECCIÓN DE LA CARGA Y COMPOSICIÓN OSEA DEL MAXILAR EN LA DISTRIBUCIÓN DE ESFUERZOS Y DEFORMACIONES POR MEDIO DE ELEMENTOS FINITOS. (*)

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PALABRAS CLAVES: Implantes dentales osteointegrados, método de elementos finitos, maxilar, implantes de rosca cuadrada, implantes de rosca tipo v, implantes inclinados, material anisotrópico.

DESCRIPCIÓN: El objetivo de este estudio es evaluar y comparar la respuesta del hueso maxilar, con una naturaleza anisotrópica, en la región alrededor del implante cuando implantes oseointegrados se posicionan en diferentes ángulos, basados en la distribución de esfuerzos y deformaciones mediante el método de elementos finitos. Nos enfocamos en modelos de implantes disponibles en el área metropolitana de Bucaramanga, Colombia. Cuarenta y cuatro modelos fueron creados para representar una porción de un hueso maxilar (región del primer molar superior) con dos tipos de implantes que tienen diferente tipo de rosca (cuadrada y en v) y material (Ti-6AL-4V ELI y titanio de grado IV). La carga de compresión axial (150 N) y la carga oblicua (150 N a un ángulo de 45 °) se aplicaron a modelos isótropos y anisótropos de los tejidos óseos. Se asume una osteointegración completa. Los resultados demostraron que el aumento de la inclinación del implante lleva a un comportamiento más crítico, especialmente para la distribución de deformaciones las cuales no pueden superar el límite de 4000 microdeformaciones. La carga oblicua es más perjudicial que la carga axial para la distribución de esfuerzos y deformaciones, además, estos se distribuyeron de manera más eficiente al usar implantes de rosca cuadrada. Los modelos isótropos propuestos en este estudio no logran representar el comportamiento de las condiciones óseas reales, las cuales son más similares a un modelo anisótropo. Los implantes de rosca cuadrada son una mejor opción para los tratamientos de implantes dentales oseointegrados, incluso cuando se requieren posiciones inclinadas. Se deben crear modelos más detallados para representar el uso de aloinjertos de hueso en un paciente que presentó reabsorción ósea.

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ABSTRACT

TITLE: COMPARATIVE FINITE ELEMENT STUDY OF THE INFLUENCE OF IMPLANT DESIGN AND INCLINATION, LOAD DIRECTION AND MAXILLA BONE COMPOSITION ON STRESS AND STRAIN DISTRIBUTION. (*)

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KEYWORDS: Osseointegrated dental implants, finite element method, maxilla bone, von Mises stress, von Mises strain, implant inclination, anisotropic material.

DESCRIPTION: The aim of this study is to evaluate and compare the response of the maxilla bone, with an anisotropic nature, in the peri-implant region when osseointegrated implants are placed in different angles, based on the stress and strain distribution by the finite element method. We focus on implant models available in the metropolitan area of Bucaramanga, Colombia. Forty-four models were created to represent a portion of a maxilla bone (upper first molar region) with two types of implants which have different thread geometry (squared and V-shaped) and material (Ti-6AL-4V ELI and grade IV Titanium). Compressive axial (150N) and oblique load (150 N at 45° angle) were applied to isotropic and anisotropic models of the bone tissues. Complete osseointegration was assumed. Results demonstrated that, the increasing of the implant inclination leads to a more critical behavior, especially for strain distribution which can not surpass the limit of 4000 microstrain. Oblique loading is more detrimental to stress and strain distribution than axial load, also, these were more efficiently distributed by squared thread implants. The proposed isotropic models in this study failed to represent the response of real bone conditions which are more similar to an anisotropic model. Squared thread implants are a better option for osseointegrated dental implant treatments, even when inclined positions are required. More detailed models should be created to represent the use of bone allografts in a patient after bone resorption happened.

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Introduction

In the field of odontology, engineering developments have generated alternatives in order to improve oral health. In the particular phenomenon of edentulism, as mentioned by Fernandez *et al*. (2016), periodontal diseases, traumatisms, orthodontic complications, endodontic failures and the common dental caries or tooth decay, can lead to the partial or complete loss of teeth, which carries health and emotional problems, affecting directly the quality of life of a person. Therefore, the use of dental implants that are inserted into the maxilla or mandible bone, is one of the most implemented alternatives as a replacement for lost teeth, with an efficacy rate of 94% and a wide variety of models to adjust to the different cases of patients who need them (Prakash, Kinikar, Gupta, Dhingra, & Rohit, 2016).

As Geng, Tan, & Liu (2001) mentioned in their literature review, Finite Elements Analysis (FEA) was first used in implant dentistry in 1976, since then, it has been used extensively to predict biomechanical performances on the implant-bone interface, due to the great amount of variations of cases in patients studied. An efficient and accurate tool as the Finite Element Method (FEM) has been used to analyze and compare the behavior of the physical problem under multiple conditions, because numerical methods provide and approximate solution by recreating it in a computer simulation (González-Estrada, Natarajan, & Graciano, 2017). Several studies in different areas of engineering, as done by Valencia, Mejía, & Erazo (2017) and Ayestarán *et al*. (2017), have shown the level of reliability of the FEM, by concluding that the values obtained in results by numerical methods are close to the experimental ones.

In the case of Colombia, a research made by the Ministry of Health & Social Protection between 2013 and 2014, showed the results of the worrying teeth loss in the population. It was found that teenagers, around 15 years old, already have edentulism, although this condition is more notorious in people between 35 and 79 years old. According to the statistics, more than 80% of the population have already lost one tooth. Also, the study concluded that women (37%) are the ones which use more dental prostheses than men (26%) (MINSALUD, 2014). Scientific research is a vital tool in order to generate solutions to the problems described above. However, based on an analysis of the production and scientific evidence in odontology journals of the countries that are part of the Ibero-American Federation of Periodontics, between 2012 and 2014, in Colombia were published just 13 articles from a total of 505 between the 11 countries which belong to the Federation, this has been increasing in the last years but still is a less explored field (Castro *et al*., 2016).

Nowadays there are people with removable prostheses dentures, but as Martín (2013) affirmed, patients with these kinds of prostheses have a lot of difficulties, from instability of the denture to lack of self-confidence. The osseointegration of dental implants offers plenty of benefits to the patient, it gives greater support to the denture, confidence when smiling and improves the esthetics (Jacobs, Vansteenberghe, Nys, & Naert, 1993). Making the decision of using dental implants must be taken under a careful analysis of the biological conditions of the patient, due to complications that may occur which can carry to a worse circumstance. Some of the criteria the dentists should study in order to choose the right treatment are the state of the lip support, related to the undesired resorption of the alveolar bone, facial profile, smile line and amplitude, upper lip length, intermaxillary relationship, bone density and soft tissue thickness (Martín, 2013).

After a tooth is lost, the alveolar bone which fulfills the function of support by maintaining the root of the teeth, starts to resorb. As Jacobs, Vansteenberghe, Nys & Naert (1993) claimed, dental implants have been used as a rehabilitation treatment for edentulous patients, counteracting the resorption of the maxilla or mandible. When a dental implant is placed, it initiates the process of osseointegration, where a direct connection between the bone and the implant is created, without presence of gingival tissue, obtaining stiffness.

The main target of the dentists and specialists in dental care is to preserve the patient's own teeth as much as they can, because the loss of these affects the patients chew ability, therefore digestive actions and swallowing gets harder and can lead to malnutrition (Musacchio *et al*., 2007). Similarly, a research done by Nascimento *et al*. (2016) has established a link between tooth loss and hypertension and obesity development, also The World Health Organization acknowledge as a disability the lack of teeth since it is a restrain for people to do their normal activities (MINSALUD, 2014).

The continuous progress of the dental implants designs has allowed the wide variety found in the market, likewise, it allowed the high rates of effectiveness in the osseointegration processes, however, there are still failures and complications due to factors such as the location of the implant, the surgical procedure and bone composition (quantity and density) (Chou, Jagodnik, & Müftü, 2008). Previous factors generate overloads which lead to weakening and loss of bone tissues, translating into implant failure, requiring it to be removed (Baggi, Cappelloni, Maceri, & Vairo, 2008).

As mentioned previously, the location of the implant is an important factor that professionals on oral rehabilitation look after, as Machtei, Oettinger-Barak, & Horwitz (2014) stated, it is a key factor in achieving satisfactory esthetics, a harmonious occlusion and peri-

implant health. The implant placement is not always as desired or ideal, because of anatomical limitations of the patient which lead to an angular placement of it and the use of angular abutments as a solution (Pellizzer *et al*., 2011). The presence of axial and oblique loads affect the distribution of stress concentration based on the angle of the implant. As Pellizzer *et al*. (2011) concluded, "The higher the implant angulation, the higher the stress value, independent of crown type" (p.436).

Similar studies have been done through the years with the purpose of analyzing the stress distribution produced by this kind of prosthetics in the mandible or maxilla bone. In Colombia, Chica, Latorre, & Agudelo (2010) and López, Laguado, & Forero (2009) research is an example of the application of FEM in dentistry with a biomechanical emphasis. Furthermore, the amount of research done to study the performance of implant inclinations is lower than the commonly FEM studies for osseointegrated implants, however we can relate to the work done by Saab, Griggs, Powers, & Engelmeier (2007) and Watanabe, Hata, Komatsu, Ramos, & Fukuda (2003).

The aim of this work is to evaluate and compare the response of the maxilla bone, with an anisotropic nature, in the peri-implant region when osseointegrated implants are placed in different angles, based on the stress and strain distribution applying the FEM, focusing on implant models from brands available in the metropolitan area of Bucaramanga, Colombia. By using the results of this study, professionals can address it in order to understand the consequences of the forces applied to osseointegrated angular placed implants, also, other researchers in biomechanics can support on the methods, parameters and the results obtained to develop it further.

The article is organized as follows: first, in the material and methods section, the experimental design is defined and the conditions are stablished, then, the two models of dental

implants are described, their properties and their mechanical design. Second, the FEM conditions are presented, the data of the maxilla bone properties, the values of the loads, the characteristics of the mesh generated and a description of the main models created. Third, in the results section are presented the von Mises stress and strain distribution for each model, the maximum values of the complete model with its location and the maximum value just in the maxilla which is the main target of this work, also, a comparison was done with isotropic models in order to evaluate its reliability.

1 Problem statement

1.1 Identification of the problem

The need to resort to oral rehabilitation treatments is a common situation in the country, where "56 percent of the national population has untreated caries" (COLPRENSA, 2014), this number is the result of a study done by the Ministry of Health along with the Javeriana University in 2014. Dental caries is one of the main causes of teeth loss, it deteriorates progressively the tissues and tooth structure, generating cavities and causing deep infections that affect the nerve which is solved by removing the tooth to prevent the infection from spreading. In addition, periodontal diseases affect the region around the tooth, if an adequate treatment is not given on time, it can lead to a decrease in the bone tissues of the maxilla and the ligaments that surrounds the teeth, as a consequence, teeth can fall by not having the necessary support.

During the IV National Oral Health Study, where more than 20,000 Colombians were clinically evaluated, it became evident that caries are present in all ages and it was concluded that "with people over 35 years old, dental loss continues to increase and it is observed that the use of both total prosthesis and partial denture is higher in the maxilla" (MINSALUD, 2014, p.195). Middle age people are considered as the most vulnerable and with the greatest recurrence to the use of dental prosthesis, being one of the most effective and implemented solutions to the problem described.

As Esquivel & Jiménez (2012) mention, "The use of conventional dentures has shown a negative impact on quality of life" (p.70), ensuring that lack of teeth affects the well-being of people from a functional as well as emotional perspective. Fixed prostheses or osseointegrated implants are a solution which need to be inserted into the bone where the root of the tooth has been completely lost, however, this type of implant treatments has several factors that determine the success or failure of the procedure.

The effectiveness of the implants is due to several factors related to its design and composition, as well as to the biological response of the patient. In the market, there is an extensive variety of designs and each one has been promoted by professionals in oral rehabilitation, who claim to use them in their procedures to obtain the best results. Thinking about the well-being of the patient, it is pertinent to analyze the biomechanical response of the bone when a dental implant is used, comparing them under the same conditions and identifying the characteristics that make a successful osseointegrated implant treatment.

1.2 Justification

The advance in prosthetic treatments has allowed the improvement and prolongation of the quality of life of people with a need to replace a limb or a part of their body. Dental implants belong to the group of prostheses that offer a solution for people who, for different reasons, have lost or must remove some of their dental pieces. The absence of teeth in the oral cavity brings with it a series of functional disadvantages, which can develop a traumatic occlusion and more inconveniences that will affect the well-being of the affected person. In the same way, aesthetic and psychological problems are generated by the discomfort of not having a complete denture.

Osseointegrated implants, when introduced into the bone structure, are characterized by good performance, durability and great similarity to real teeth. Therefore, they are one of the most implemented and developed alternatives currently by professionals in oral rehabilitation. There is a great variety of this type of implants in the market to achieve the same goal, however, their structural characteristics, materials and finishes used will differentiate them, since these variables influence on the results, once they are adapted and positioned in the patient's maxilla.

As a contribution to the university community, the School of Mechanical Engineering and the citizens of the metropolitan area of Bucaramanga, the biomechanical analysis of the bone response after placing some implants used by professionals in the region, employing the finite element method as a study tool, will be beneficial to establish a true criterion about how some variations as the implant thread geometry, material properties inclination and bone composition alters its performance.

2 Objectives

2.1 General objective

To evaluate and compare the performance of the maxilla bone, with an anisotropic nature, in the peri-implant region when osseointegrated implants, used in Bucaramanga (Colombia), are placed in different angles, based on the stress and strain distribution applying the FEM.

2.2 Specific objectives

- Generate the three-dimensional geometric models of the maxilla bone structure to be studied, maintaining its real properties, using a segmentation software and a computed axial tomography (CT) of a patient who needed an osseointegrated implant.
- Modeling in Solidworks® the different dental implants used in local dental clinics in the metropolitan area of Bucaramanga.
- Simulate the implant-bone interaction for the biomechanical study, through the FEM under multiple load conditions.
- Compare the performances of the implants in the simulations created, analyzing the stress and strain distributions caused in the bone with anisotropic and isotropic properties.

3 Methodology

Several studies done over the last few years sustain that the failure rate of implants used in the maxilla bone is higher than in the jawbone (Chaves Gómez, Grageda Núñez, & Ubribe Querol, 2015) (Slagter, Raghoebar, Bakker, Vissink, & Meijer, 2016) (Omran, Miley, McLeod, & Garcia, 2015). Based on the results found, the analysis was developed in the maxilla, in order to generate a critical condition and, consequently, obtaining more notorious results with remarkable differences between the different implants.

One of the determinant factors for successful dental implants treatments is the dynamic process of osseointegration, after the placement of the implant in the bone begins the healing phase which is vital to the implant stability because in a first place, the link is just mechanical, not biological, so the implant should allow the generation of new bone cells that provide rigidity (Bosshardt, Chappuis, & Buser, 2017). As the present study is based on the FEM, we assume a complete osseointegration between implants and natural tissues as previous studies have stablished (Baggi *et al*., 2008) (Kaleli, Sarac, Külünk, & Öztürk, 2017) (Pérez *et al*., 2016).

The portion of maxilla bone selected from the computer aided tomography of the patient was modeled as an anisotropic material, based on the density provided by the data of the CAT scan, so the results are as approximate as possible to real conditions. Also, a simplified model was created in a CAD software as research done before, with isotropic properties in order to evaluate if it is necessary to develop more complex models for accurate results.

3.1 Experimental design

For this research, a total of forty-four 3D models were proposed, considering the following study factors: multiple angular placements of the dental implants and its variations based on their material and mechanical design, the effect of the loading type: axial and oblique loading, and the effect of the bone composition: isotropic and anisotropic. The response variables were the stresses produced by the loads on the peri-implant bone which correspond to the region of the upper first molar.

3.2 Segmentation of the bone

In order to develop the analysis by the FEM, a particular study case was considered. A female patient around fifty years old, who suffered a fracture in an upper first molar and went under surgery to remove the tooth (Figure 1). The quality and quantity of the bone in the area of the missing tooth was acceptable to pursue a dental implant treatment, also, the patient already has gone under treatment and has an osseointegrated implant which provides reliability. Furthermore, the case was analyzed with help provided by the dentist and the verdict was checked by following the Zarb & Lekholm (1985) bone classification, obtaining a Type II bone. The bone quality classification system based on Hounsfield scale is as follows: Type I bone is homogeneous compact bone (>1250 HU), Type II bone is when a thick layer of compact bone is surrounding a dense trabecular bone core (750-1250 HU), Type III bone is when a thin layer of cortical bone is surrounding a dense trabecular bone core (375-750 HU) and Type IV bone is

when a thin layer of cortical bone is surrounding a low density spongy bone core (<375 HU) (Moya-Villaescusa & Sánchez-Pérez, 2017) (Gulsahi, 2011).

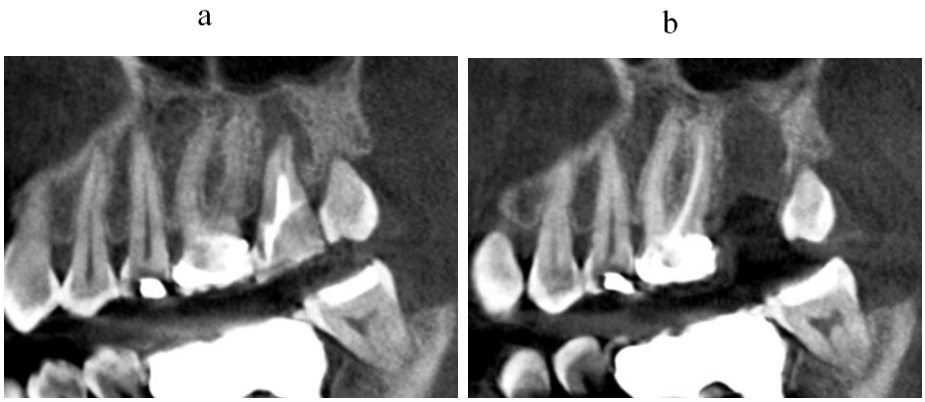

Figure 1. (a) Upper first molar fracture of the patient selected and (b) maxilla condition after its removal.

The segmentation began with the definition of the area to take in consideration for the analysis. As recent studies done by Djebbar, Serier, & Bachir Bouiadjra (2017), Minatel *et al*.(2017) and Dos Santos, Meloto, Bacchi, & Correr-Sobrinho (2017), proposed that the portion of the maxilla selected was the area where the tooth was absent, in this study, the portion corresponds to the region of the upper first molar.

3.3 Dental implants

After looking for the most used dental implants in Bucaramanga by visiting the local odontology clinics and asking to the professionals, the following brands were mentioned: Zimmer Biomet, BioHorizons, GMI-Ilerimplants Group and Straumann. Each one of the previous manufacturing houses has its differences in designs, materials and objectives but for the

main purpose of this study, were selected two of the brands based in their popularity. Thus, as a result, the dental implants modelled are from BioHorizons and GMI-Ilerimplants Group.

The following information was obtained directly from the catalogues of the two manufacturing houses selected previously, which provides the material and some of its characteristics (GMI Ilerimplant-group, 2017) (Biohorizons, 2017). The model selected from BioHorizons is a Mount-free Tapered Internal Implant, reference TLX3409, which is made from a Titanium Alloy (Ti-6AL-4V ELI) providing a higher maximum resistance and limit of elastic behavior, which the company claims as more resistant to fractures and propagation of fissures by fatigue. On the other hand, the model from GMI-Ilerimplants Group is a GMI frontier internal connection hexagonal implant, reference KDA0F3602, machined in CP grade IV Titanium, being one of the most common materials employed.

Table 1

Material properties of the dental implants

Brand	Reference	Material	Modulus of Elasticity [GPa]	Poisson's Ratio
BioHorizons	TLX3409	Ti-6AL-4V ELI	120	0.31
GMI	KDA0F3602	CP grade IV Titanium	110	0.35

Based on literature about dental implants and their stress distribution by a FEA model, the data needed about the materials of the implants are the Young's modulus (*E*) and the Poisson's ratio. The values shown in Table 1, were taken from previous studies and catalogues from

companies that distribute the materials (Alencar *et al*., 2017) (Rand, Kohorst, Greuling, Borchers, & Stiesch, 2016) (Niinomi, 1998) (United Performance Metals, 2015).

Beside the material properties differences of the two implants selected for this study, the geometrical design spotlights as a differential feature. The TLX3409 (Figure 2 a) has an external square thread which provides higher functional surface area translating into higher bone-implant contact, this is desired in order to dissipate compressive and tensile load to the bone for stability. As Meirelles, Brånemark, Albrektsson, Feng, & Johansson (2015) stated in their study, square threads demonstrated greater bone contact compared with standard v-shape and reverse buttress threads. Instead, the thread design of the KDA0F3602 (Figure 2 b) implant is a v-shape. Both designs have self-threading millings and slight tapering which facilitate the insertion and reduce the tension at the bone-implant interface (GMI Ilerimplant-group, 2017).

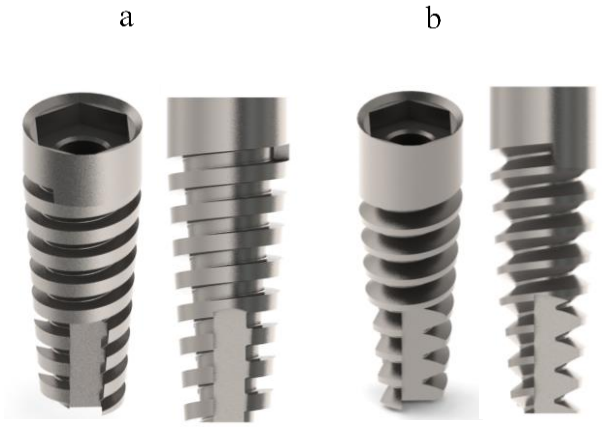

Figure 2. Isometric and lateral view of the (a) TLX3409 and (b) KDA0F3602 three-dimensional solid models.

The dimensions of the implant that the patient requires, recommended by the professional, is a 3.5mm diameter and 9.5mm in length. These dimensions can slightly change because it depends on the manufacturing house, if they have this particular configuration. Hence, by following the

recommendations of the professional, based on the previous assessment, the dimensions of the two implant references were selected (Table *2*) in order to approach the initial requirements which are ideal.

Table 2

Dimensions of the dental implants selected

Reference	Diameter [mm]	Lenght [mm]
TLX3409	3.4	9.0
KDA0F3602	3.3	10.0

3.4 Loading

As an initial force, during the procedure of inserting the implant, a torque is applied in order to tight it to the bone, the value of this force varies accordingly to the manufacturing house and for the purpose of this study its effects are not considered. On the other hand, the implants support occlusal forces during its functional phase, the axial or vertical force represents the normal chewing ability which is the masticatory force, while the oblique force signifies a special masticatory force, due to eating irregular food (Cheng et al., 2017). Table 3 displays the values of axial and oblique loads employed in studies done before, the data shows that the most used values are in the range between 50N and 150N for the axial load, while in the oblique load, this range is between 100N and 150N. Furthermore, in Alencar *et al*. (2017), [35], masticatory forces can reach a peak of 350 N in posterior teeth. Considering the previous information, in this

particular study the axial load applied is 150N and the oblique load is at a 45° angle relatively to the implant axis with a magnitude of 150N, keeping the values in both ranges found.

Figure 3 shows the forces applied to the abutments of the implants, which have the same material properties as them, notice that the oblique load is applied in the direction of the implant inclination. As boundary conditions, fixed supports were applied to the lateral faces of the models which are restricted by the rest of the maxilla.

Table 3

Load values applied in previous FEM studies for dental implants.

Authors	Axial Load	Oblique Load (45°)
Anitua *et al*. (2010)	114N	-
Cheng *et al*. (2017)	500N	500N
(Chica et al., 2010)	-	1N
Geng *et al*. (2004)	-	141N
Macedo *et al*. (2017)	150N	150N
Minatel *et al*. (2017)	50N	-
Pellizzer *et al*. (2011)	100N	100N

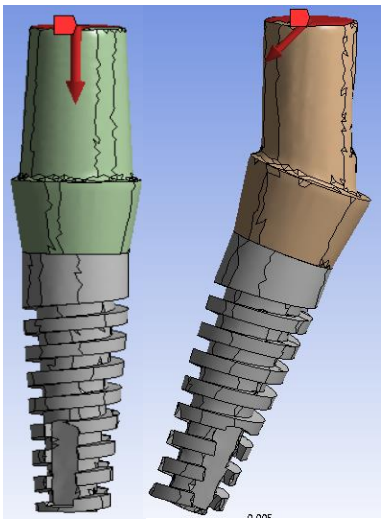

Figure 3. Example of two models indicating the directions of the forces applied to the implants.

3.5 Finite element models

Four main models are built as shown in figure 4, the other forty are a variation of these. The models similar to the Figure 4 (a) are anisotropic with the presence of a cylinder with a 6GPa Young's modulus cortical bone because it represents the new tissues created after filling the empty space produced by teeth loss, with bone allografts. This is an attempt to produce a more detailed model, closer to a real condition when it is necessary to fill the gap on the bone in order to proceed with the implant treatment. Figure 4 (b) is the representation of two type of models without allografts, the first has anisotropic properties, while the second one is a complete cortical isotropic bone with a Young's modulus of E=13.7 GPa. Most dental implants studies with FEM are developed under isotropic and ideal conditions, which may not relate to real cases because bone composition is almost unique for each patient, due to it, Figure 4 (c) represents an ideal isotropic model created in a CAD software as in previous research, it has the properties of a Type

II bone following the classification of Zarb & Lekholm (1985). What is expected from this comparison is to conclude if a simplified model provides a good level of accuracy in the values and behavior of the von Mises stress and strain in the bone

Anisotropic models have 10 different materials, its distribution and Young's modulus values are given by the density obtained from the CAT scan. For the previous bone structures are placed the two different implants in three positions (0°, 15° and 20°) with the axial and oblique loads.

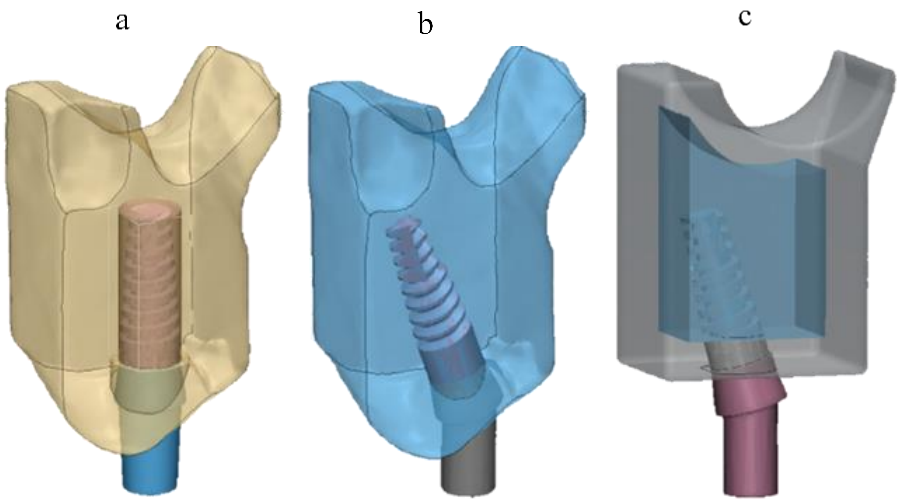

Figure 4. FE models developed: (a) anisotropic model taken from the CAT SCAN with cortical bone allograft, (b) anisotropic/isotropic model taken from the CAT SCAN without allografts and (c) ideal isotropic model.

In order to facilitate the reading and interpretation of the results, the types of models are described in Table 4.

Table 4

Name and description of model's variation based on the bone properties.

Models	Description
Type 1	Anisotropic with cylinder of cortical bone
Type 2	Anisotropic bone
Type 3	Complete cortical isotropic bone
Type 4	Ideal cortical and trabecular Isotropic bone

The meshing of the models was done in the 3 Matic software, using linear tetrahedrons with 8 nodes (SOLID185). Three types of meshes were tested in order to ensure that the numerical results were mesh-independent. The first mesh has 3566 nodes and 13061 elements with an edge length of 2mm, the second mesh has 43093 nodes and 160537 elements with an edge length of 1mm and the last, which is the one used for the models, has 282046 nodes and 1696314 elements with an edge length of 0.3mm. It was proven that the maximum von Mises stress and strain values converged toward a finite value as the mesh density increased, indicating that further refinement of the mesh would not affect the results. As an example of the quality of the mesh, Figure 5 shows a superficial and volumetric mesh for one of the models.

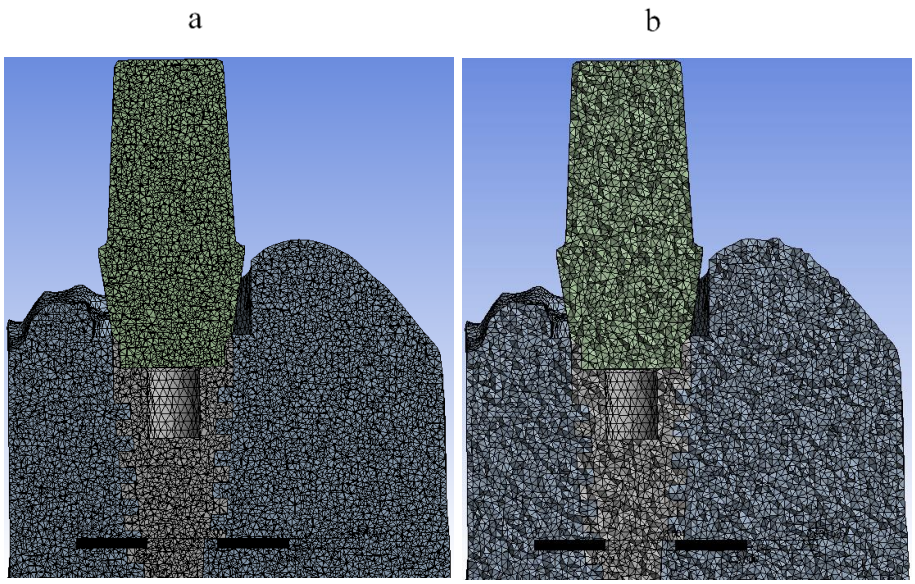

Figure 5. Detailed view of the (a) superficial and (b) volumetric mesh of the models.

The nodes and elements of the meshes were calculated for each model, these were grouped according to type of bone and implant reference used. Table 5 shows the correspondent averaged values of nodes and elements for each group.

Table 5

Average number of nodes and elements of the meshes according to the implant and type of bone

Implant Reference	Type of Bone	Nodes	Elements
TLX3409	CAT scan Bone	283132	1695533
	CAD Bone	386446	2282128
KDA0F3602	CAT scan Bone	284616	1700050
	CAD Bone	389208	2292754

As mentioned previously, the models were created as anisotropic and isotropic. For the anisotropic models, 10 different materials were assigned in a range between 500 MPa and 15000 MPa, which have been the lowest and highest values of the Young's modulus for trabecular and cortical bone used in previous studies(Baggi et al., 2008)(Macedo et al., 2017). Cortical bone starts with a Young's modulus of 1370 Mpa, hence, material with a lower value correspond to trabecular bone. The distribution was based on the Hounsfield scale of the CAT scan which relate to the density of the maxilla.

Saab *et al*. (2007) presents some of the Young's modulus values employed in previous studies for both cortical and trabecular bone for isotropic models. For the cortical bone, the most common value is 13700 MPa, while for the trabecular bone, the values used are in a range from 500 MPa to 2000 MPa, being 1370 MPa the most common. For the ideal isotropic models the most used values mentioned before were used. Also, in this study, new hard tissues, represented as the cylinder in Type 1 models, has a Young's modulus of 6000 MPa. Lastly, all bone materials have a Poisson's ratio of 0.3.

4 Results

The data obtained are the values of the stress and strain (according to the von Mises yield criterion) caused by the applied loads. Based on the study developed by Saab *et al*. (2007) the physiologic strain limit is 4000 microstrain, more than this is considered to be pathologic.

Furthermore, following the statements of Baggi *et al*. (2008), for a compressive stress modulus, the maximum value in the cortical bone should not exceed 190 MPa, while for the trabecular bone is 5 MPa. These values are a reference to analyze the behavior of the load distribution in the maxilla, remembering that overload may cause bone resorption or fatigue failure of the implant (Geng et al., 2001).

To facilitate the interpretation of the data, the results are organized by type of implant for Type 1 and Type 2 models, then is a comparison with isotropic Type 3 and Type 4 models. In the other hand, due to the number of elements with cortical bone properties in anisotropic models, being the majority as shown in Figure 6, and its location in the peri-implant region, for these models were only taken in consideration the limit of 190 MPa for stress values as an analyzing reference, but it is clear that they are not restricted to cortical tissues, trabecular bone also absorbs the stresses. This may motivate future researchers to generate new studies analyzing trabecular bone response in anisotropic models.

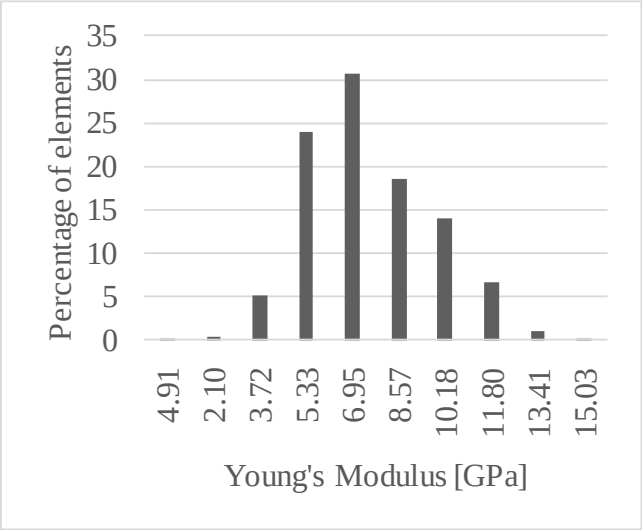

Figure 6. Distribution of the 10 materials according to the Young's Modulus in the elements of anisotropic models.

As a first glimpse of the results, the majority of the models under the oblique load of 150 N fail. Highest values of von Mises stress and strain may be alarming because they surpass the limits stablished and they can be higher than in works done before. Although, the highest values obtained in this study are due to the magnitude of the load applied, hence, a Type 2 model is selected in order to verify the response of the bone when the load is reduced. Table 6 shows how the von Mises stress and strain peak values increases when the load does too, in a range until 70 N none of the models fail. In this study, peak values are not as important as the understanding of the distribution of the stress and strain being the reason why a critical load is applied in order to see clearly how the bone would respond.

Table 6.

Maximum von Mises stress and strain values just for the maxilla for the Type 2 model with a 20° incline TLX3409 implant, under different oblique load values.

Oblique load [N]	Max Stress [Pa]	Max Strain [m/m]
30	3.24E7	1.10E-3
70	7.58E7	2.58E-3
150	1.62E8	5.50E-3

4.1 TLX3409 implant

The firsts results correspond to the Type 1 models with the squared thread implants. Table 7 shows the maximum values of stress and strain with its location in each model.

Table 7

Maximum von Mises stress and strain values in the model, indicating its location, and maximum values for the maxilla for Type 1 models with TLX3409 implants.

			Inclination		
			0°	15°	20°
Axial	Max stress [Pa]	Model	4.91E7 (C)	1.19E8 (C)	1.59E8 (C)
		Maxilla	4.91E7	1.18E8	1.59E8
	Max strain [m/m]	Model	1.43E-2 (A)	1.51E-2 (A)	1.83E-2 (A)
		Maxilla	9.42E-3	5.58E-4	1.42E-3
Oblique	Max stress [Pa]	Model	3.53E8 (C)	4.49E8 (C)	5.30E8 (C)
		Maxilla	3.53E8	4.48E8	5.30E8
	Max strain [m/m]	Model	1.25E-1 (A)	7.89E-2 (A)	7.43E-2 (A)
		Maxilla	6,78E-2	4.22E-3	4.84E-3
Abutment (A) Cylinder (C) Implant (I) Maxilla (M)					

After analyzing and comparing the results, is notable the differences between the values obtained under axial and oblique loads. None of the models (0°, 15° and 20°) under axial load exceed the limit of stress for cortical bone (1.9E8 Pa) and the maximum is located at the cylinder surface. The maximum values of strain are higher than the limit for the bone 4000 microstrain, but these are located in the abutment, as the maximum do not relate to the maxilla it is necessary to verify strain values just for it, which includes the cylinder of cortical bone. Under oblique load, the highest stress value is 530 MPa for the model with the implant at a 20° inclination, it is located at the top of the cylinder, this peak occurs in an inflection point caused by the direction of the force, as the inclination increases the stress does too in the same region. The high values can appear due to a distortion of the mesh in that point.

As Figure 7 shows, for the angle positions, strain values are under the physiologic limit for the (b) 15° and (c) 20° models, while the (a) vertical one exceeds it.

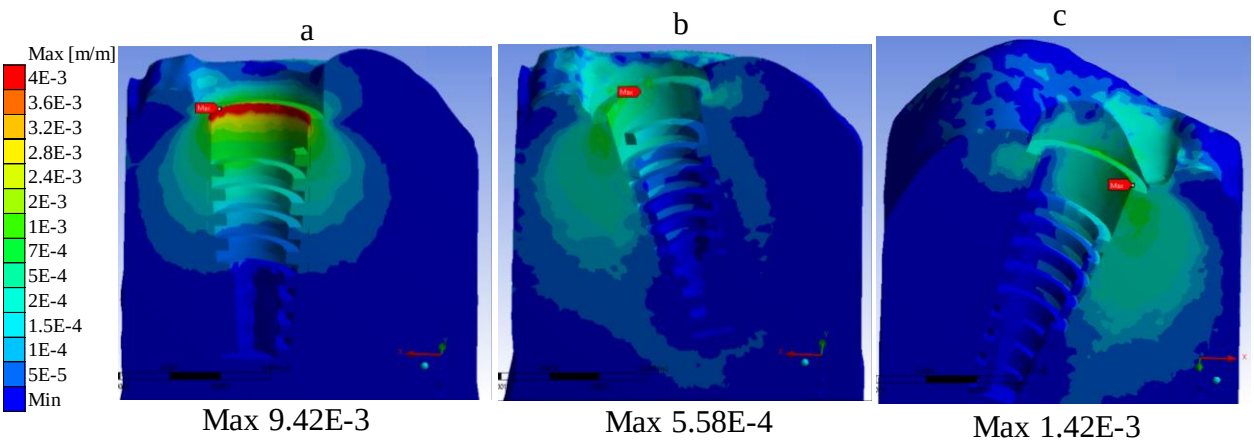

Figure 7. Von Mises strain results on the maxilla with a TLX3409 implant for (a) 0°, (b) 15° and (c) 20° inclination under axial load in Type 1 models.

The model (a) with the vertical position of the implant was not expected to surpass the limit of the strain value because it is the ideal position of the implant. The variables between these models are their inclination and their location in the maxilla, the vertical one is located slightly deeper than the others but it is not considered as a significant variation to cause the failure. The strain distribution in the vertical model is symmetrical as shown in the previous Figure 7 (a) and more concentrated, near to the apex of the implant, while the inclined models show a lateral and wider distribution of the strain to the left middle side. The reason for this behavior is that the peri-implant region tends to have higher Young's modulus cortical bone, which explain the concentrated strain in the model (a), meanwhile the inclination produces a lateral distribution to the middle region presents a lower value of Young's modulus and spreads the deformation without reaching the limit allowed. The strain distribution along an inclined implant under the axial load tends to create an inflection point in the surface where occurs the contact between the abutment and the implant, being it the cause of its particular behavior.

Type 1 models under oblique load of 150N at a 45° fail in both stress and strain. The behavior is similar to the models under axial load because stress keep being maximum in the cylinder top region and the strain in the abutment, but all values are higher, this verifies conclusions and claims of previous studies about the oblique load being more critical than the axial (Geng et al., 2001) (Cheng et al., 2017) (Watanabe et al., 2003). Figure 8 presents the results obtained of stress and strain for each Type 1 model under the oblique load.

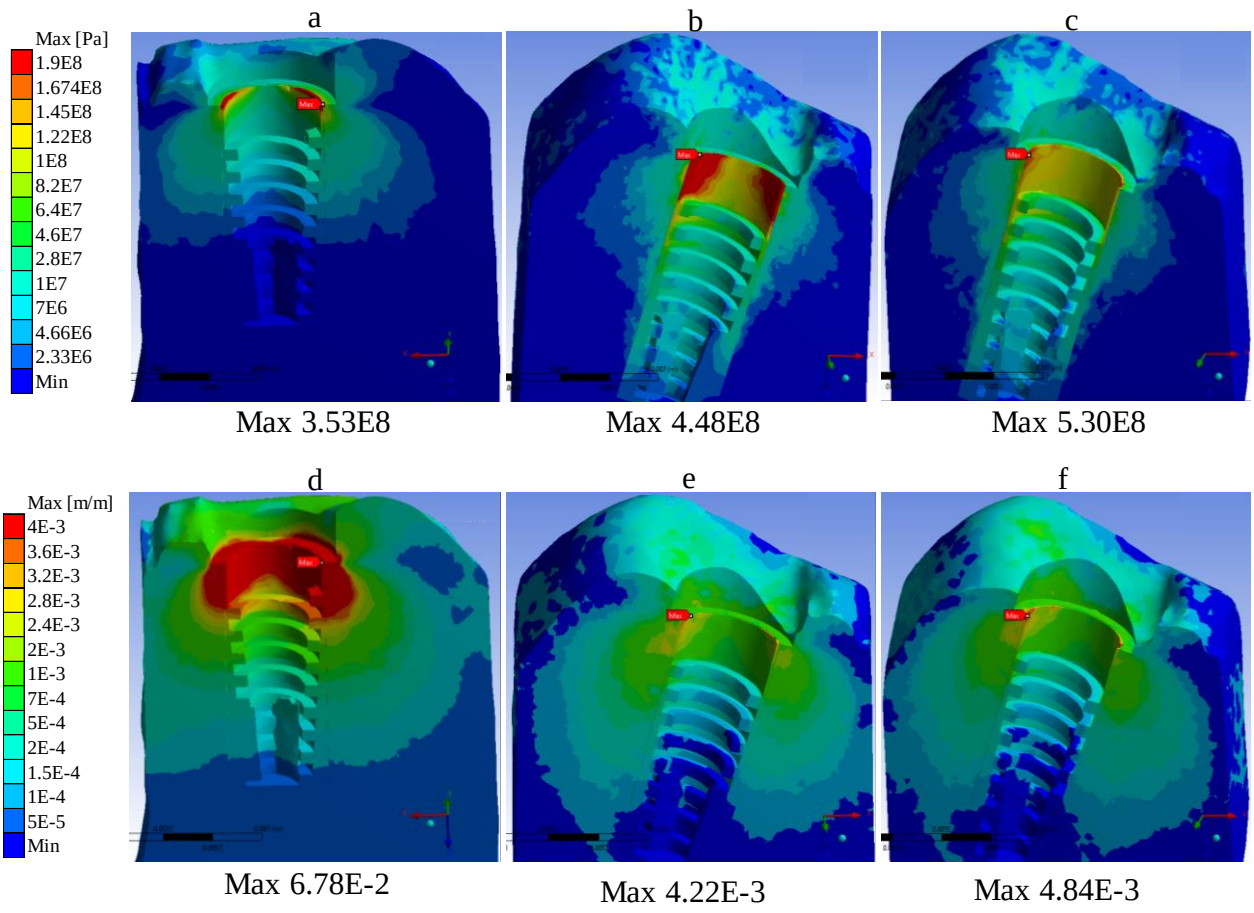

Figure 8. Von Mises stress results for (a) 0°, (b) 15°, (c) 20° inclination and von Mises strain results for (d) 0°, (e) 15° and (f) 20° inclination, on the maxilla with a TLX3409 implant under oblique load in Type 1 models.

As Figure 8 shows, the vertical positioned implant (a) presents the smallest region of stress which surpass the limit for cortical bone while in the strain distribution (d) it shows the biggest region of problematic values. Under oblique loads, all the models exhibit a symmetrical distribution of stress and strain, which did not happen under the axial load for the models with inclined implants because the force was not directed towards the long axis of them. Both 15° and 20° inclined models present a similar behavior, with a wider distribution of stress and a focused strain distribution with punctual peak values. The maximum von Mises stress value in the maxilla is 530 Mpa which occurs in the 20° inclined model, as mentioned before, the high stress peaks can be attributed to a distortion point of the cylinder mesh, on the other hand, maximum strain is Due to the similar behavior of the inclined implants, could be considered that the 5° angle difference between them do not alter significantly the results, so for posterior studies, a higher or lower angle should be study in order to avoid results alike and obtained more useful data.

The next type of models analyzed are the Type 2 with squared thread implants, Table 8 presents the maximum values for both loads as done before.

Table 8

Maximum von Mises stress and strain values in the model, indicating its location, and maximum values for the maxilla for Type 2 models with TLX3409 implants.

			Inclination		
			0°	15°	20°
Axial	Max stress [Pa]	Model	5.92E7 (I)	6.90E7 (M)	9.49E7 (M)
		Maxilla	3.67E7	6.89E7	9.44E7
	Max strain [m/m]	Model	7.35E-3 (A)	1.24E-2 (A)	1.13E-2 (A)
		Maxilla	9.29E-4	1.32E-3	2.81E-3
Oblique	Max stress [Pa]	Model	2.90E8 (I)	3.67E8 (I)	4.47E8 (M)
		Maxilla	1.99E8	2.18E8	1.62E8
	Max strain [m/m]	Model	7.19E-2 (A)	6.14E-2 (A)	6.11E-2 (A)
		Maxilla	5.80E-3	5.07E-3	5.50E-3

Abutment (A) Implant (I) Maxilla (M)

As models Type 1 revealed, the maxilla with anisotropic nature do not fail under axial load for stress nor strain, the only exception was the Type 1 vertical implant model which surpassed the strain limit. Due to the success of the bone performance under the axial load, only results for oblique loads would be analyzed for now on in order to present critical conditions. .Figure 9 shows the stress and strain results for each Type 2 model under oblique load.

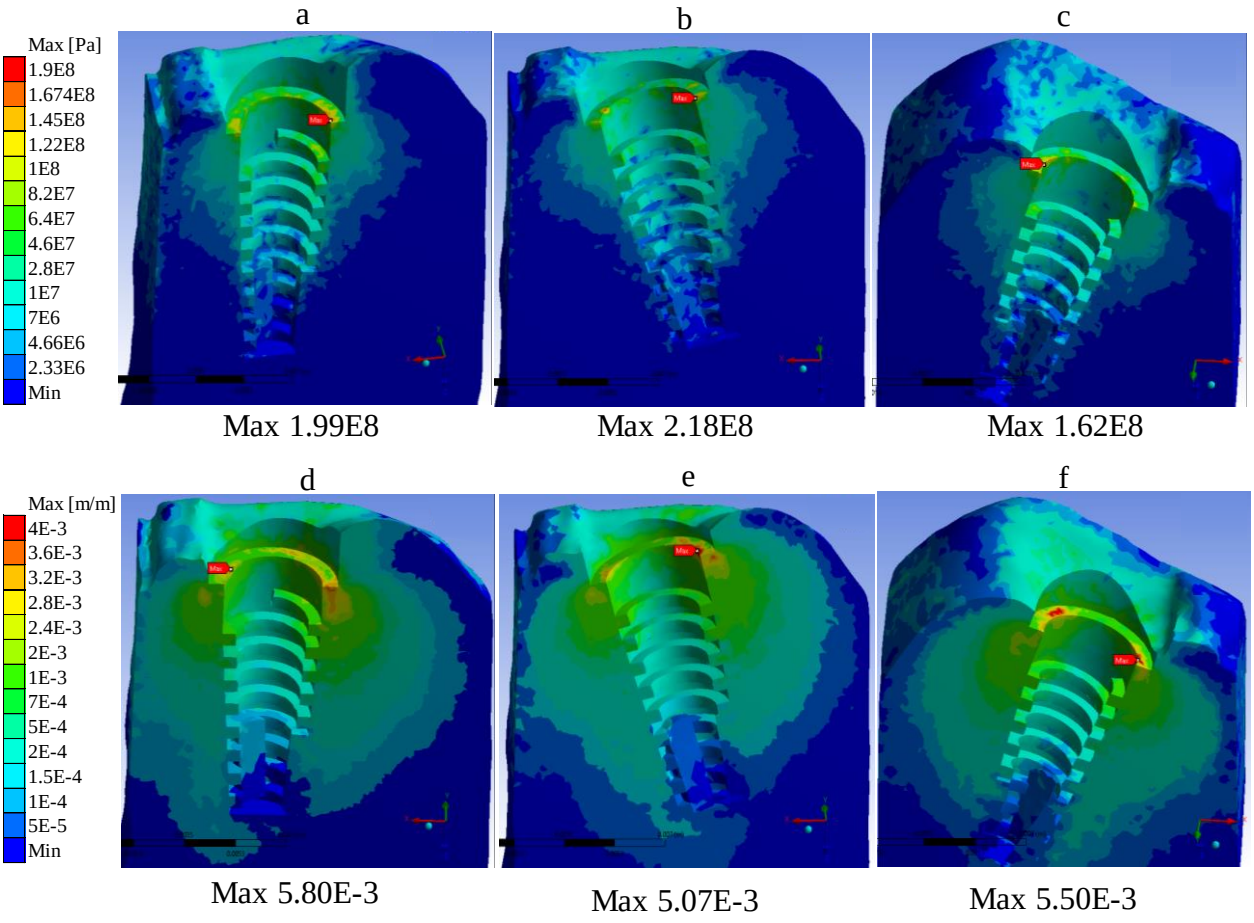

Figure 9. Von Mises stress results for (a) 0°, (b) 15°, (c) 20° inclination and von Mises strain results for (d) 0°, (e) 15° and (f) 20° inclination, on the maxilla with a TLX3409 implant under oblique load in Type 2 models.

As seen in the previous results, all models exceed the permissive von Mises stress and strain values which translates in a failure. The problematic points of each model (a, b, c) are located almost in the same place of the peri-implant region and are very specific, the absence of bone allograft allows a better distribution of the load along the axis of the implants. This comparison keeps leading to the claim that the elements of bone tissues in the peri-implant region have a higher Young's modulus, being it the reason why these models resist the load more efficiently

that the ones with bone tissues grown after osseointegration after using allografts. The distribution is symmetrical in the three models and the 15° inclined implant models presents the highest stress of 2.18E8 while the 0° inclined implant show the highest strain of 5.80 microstrain.

The strain distribution results present a more similar behavior between the models than the obtained for the Type 1. Despite of peak values, the 20° inclined implant model is the more critical because of its bigger regions with elements that surpass the physiological limit, represented in red (Figure 9 f).

4.2 KDA0F3602 implant

The results presented in Table 9 corresponds to the model Type 1 with V-shaped thread implants. It shows the maximum von Mises stress and strain values as previous tables.

Table 9

Maximum von Mises stress and strain values in the model, indicating its location, and maximum values for the maxilla for Type 1 models with KDA0F3602 implants.

			Inclination		
			0	15°	20°
Axial	Max Stress [Pa]	Model	3.01E7 (C)	7.97E7 (C)	9.99E7 (C)
		Maxillar	3.01E7	7.97E7	9.99E7
	Max Strain [m/m]	Model	4.98E-3 (A)	1.07E-2 (C)	3.16E-2 (A)
		Maxilla	4.54E-3	1.07E-2	1.75E-2
Oblique	Max Stress [Pa]	Model	2.82E8 (A)	3.15E8 (C)	2.95E8 (C)
		Maxilla	2.79E8	3.15E8	2.95E8
	Max Strain [m/m]	Model	4.81E-2 (A)	4.52E-2 (A)	4.16E-2 (A)
		Maxilla	4.61E-2	4.29E-2	4.11E-2

Abutment (A) Cylinder (C) Implant (I) Maxilla (M)

In the case of axial load none of the models exceed the stress limit for cortical bone. However, all the models surpass the maximum strain limit, the models of 0° and 20° exhibit their maximum value in the abutment what compels to check if the strain value in the maxilla or the cortical bone cylinder is higher than the strain limit. As Figure 10 shows, all the three models surpassed the physiological strain limit value.

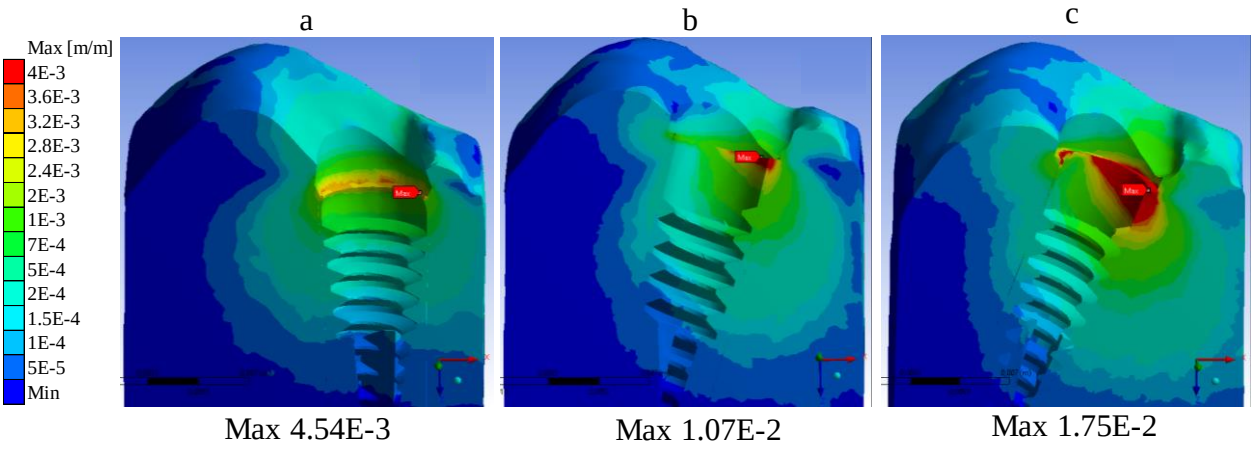

Figure 10. Von Mises strain results on the maxilla with a KDA0F3602 implant for (a) 0°, (b) 15° and (c) 20° inclination under axial load in Type 1 models.

After comparing Type 1 models with both types of implants it is found a noticeable difference between them. While the models with TLX3409 only present an unexpected strain concentration in the vertical model (Figure 7 a), all of the KDA0F3602 exceed the limit and show significant problematic regions. Because of the location of the maximum strain in the models at the upper region, the diameter and length variation between the implants are not considered as a cause for their different behavior, it is important to highlight the fact that the length difference is only 1mm while the diameter is just 0.1mm. Therefore, the critical factor for the KDA0F3602

model's failure could be its material properties with a Young's modulus of 110 GPa, being 10 GPa less than the TLX3409 ones which translates in more load transfer to the bone or the geometry thread.

The show the results for the previous models under the oblique load. As the models fail under axial load after claiming that it is not a critical force, the failure under oblique load is expected. All the models surpass the limits for stress and strain, maintaining the peri-implant region as the critical zone. Type 1 model with the vertical implant (a) exhibits a similar behavior to the Type 1 model with the TLX3409 implant (Figure 8 a), showing a small region of problematic stress values in the cylinder, while having a bigger region with strain failure.

The behavior obtained for the stress(Figure 11 b, c) and strain (e, f) are the opposite to the results for the same kind of models with squared thread implants (Figure 8). As is known, the strain is the deformation due to the stress distribution in a body after a force is applied, so a better stress distribution will lead to a lower strain concentration, which is the case for the TLX3409 implants. The V-shaped thread implants generate a wider region of critical strain values because the stress is focalized in specific points at the peri-implant region, even though the maximum values in the V-shaped implants models are lower than in the squared ones. At Figure 8 (b) and (c) it is shown how the stress is more distributed along the bone. The results validate the affirmation done in previous studies as the one done by Steigenga, Al-Shammari, Misch, Nociti, & Wang (2004) that squared threads dissipate more efficiently the load to the bone which is desired in order to obtain more contact to the implant surface, generating stability,

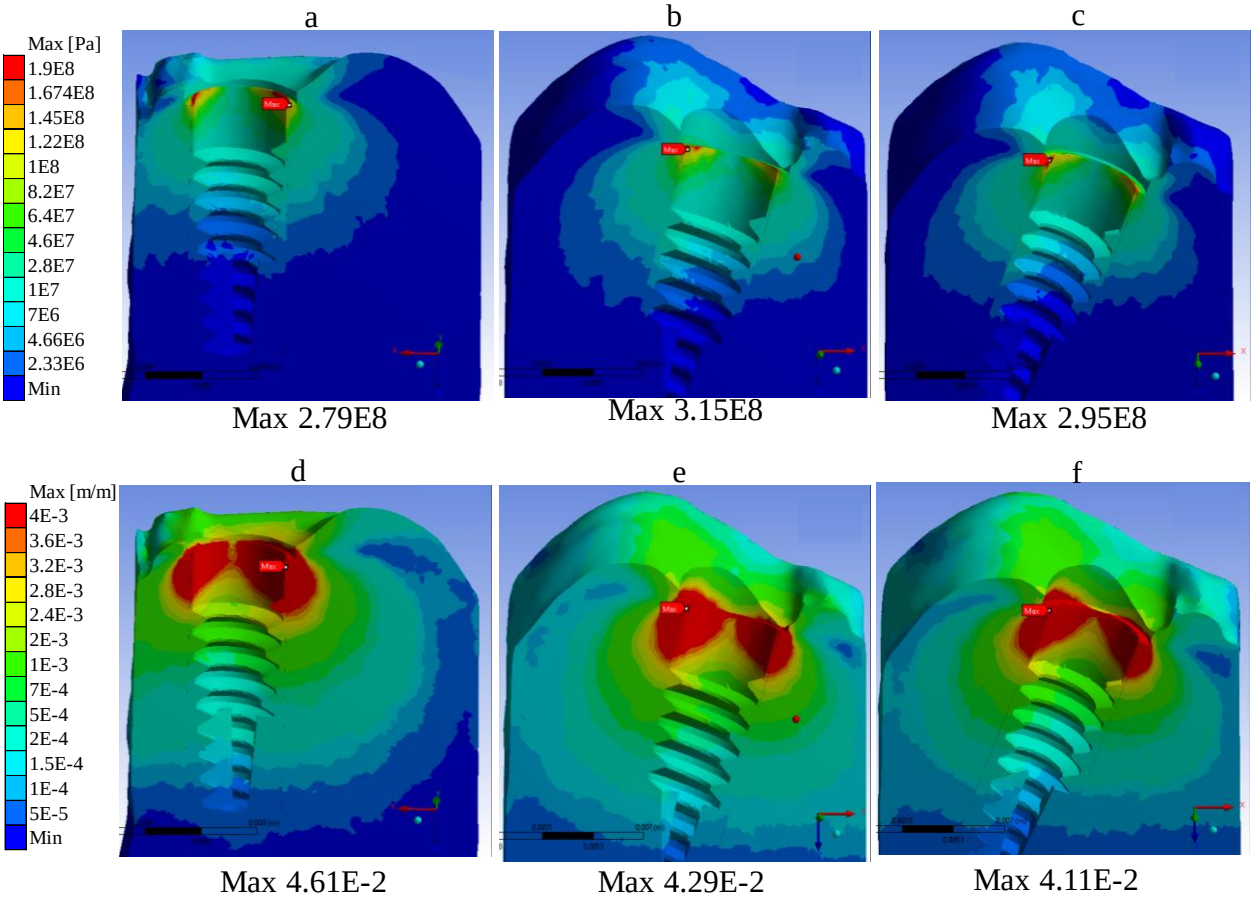

Figure 11. Von Mises stress results for (a) 0°, (b) 15°, (c) 20° inclination and von Mises strain results for (d) 0°, (e) 15° and (f) 20° inclination, on the maxilla with a KDA0F3602 implant under oblique load in Type 1 models.

The information introduced in Table 10 corresponds to the model Type 2 results for maximum von Mises stress and strain values likewise its location.

The maximum stress values under axial load are under the limit of 1.9E8 MPa so these models do not fail, but for strain distribution all of the models present a maximum value above the 4000 microstrain which lead to a verification of values in the maxilla.

Table 10

Maximum stress and strain value for model type 2 of KDA0F3602 implant

			Inclination		
			0°	15°	20°
Axial	Max Stress [Pa]	Model	7.65E7 (M)	1.09E8 (A)	1.41E8 (I)
		Maxilla	7.65E7	9.57E7	1.36E8
	Max Strain [m/m]	Model	1.29E-2 (I)	4.25E-3 (A)	1.12E-2 (I)
		Maxilla	8.9E-4	1.62E-3	7.4E-3
Oblique	Max Stress [Pa]	Model	8.21E8 (M)	4.46E8 (I)	5.2E8 (A)
		Maxilla	8.21E8	2.76E8	3.74E8
	Max Strain [m/m]	Model	7.03E-2 (M)	2E-2 (A)	3.98E-2 (I)
		Maxilla	7.03E-2	4.54E-2	1.85E-2
Abutment (A) Implant (I) Maxilla (M)					

Figure 12 present the strain distribution for Type 2 in each inclination under axial load, unlike the Type 2 models with squared thread implants where none of them fail under axial load for strain, in this case, the 20° (c) inclined implant model surpass the limit in the peri-implant region. The difference between the 15° and 20° inclined implant models is a lot more noticeable which refutes the previous claim about 5° not being a relevant variation.

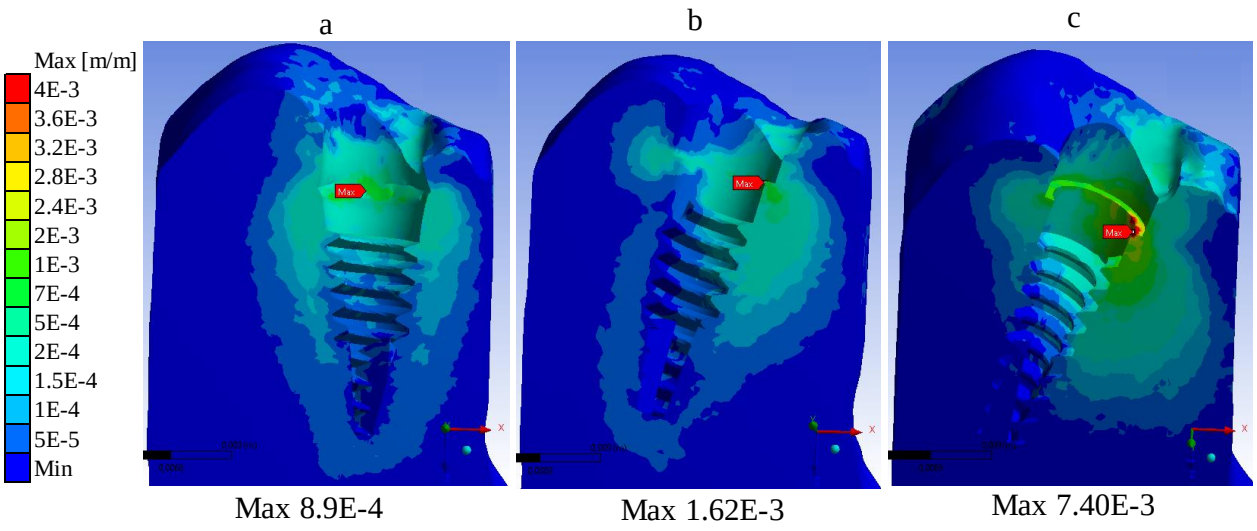

Figure 12. Von Mises strain results on the maxilla with a KDA0F3602 implant for (a) 0° (b) 15° and (c) 20° inclination under axial load in Type 2 models.

Under oblique load, all the maximum values surpass the limit and is necessary to check the distributions at the bone tissues. Figure 13 presents the stress and strain distribution for each model. The results keep validating the fact that oblique and also a higher inclination of the implant produces a critical performance in the maxilla. In comparison to Figure 9 results which corresponds to the Type 2 models with square thread implants, they affect the bone in a similar way, concentrating stress and strain peaks at the peri-implant region and distributing the load along the contact surface in a symmetrical way. Although, the V-shape thread implants produce wider regions of critical values for both stress and strain which means that this kind of thread geometry is less efficient.

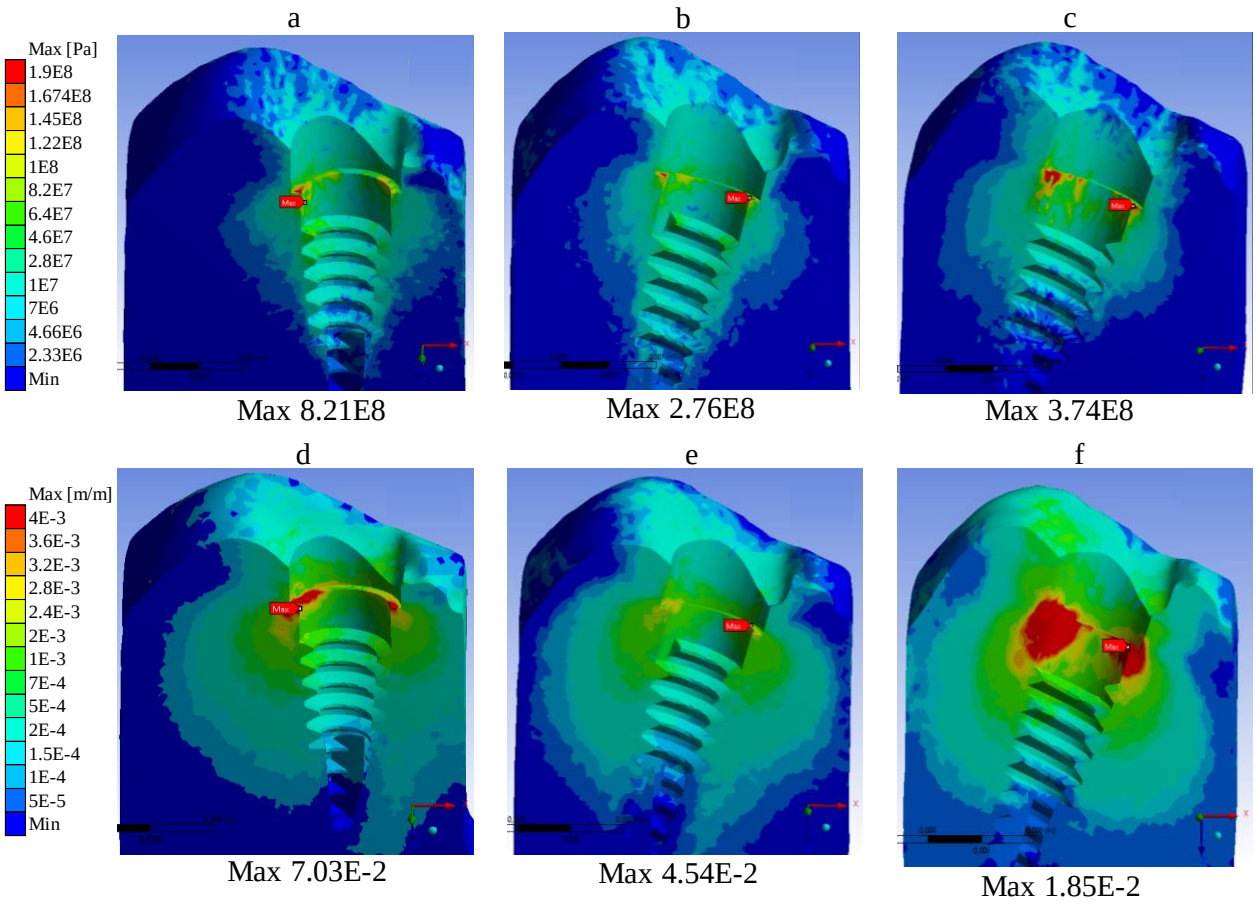

Figure 13. Von Mises stress results for (a) 0°, (b) 15°, (c) 20° inclination and von Mises strain results for (d) 0°, (e) 15° and (f) 20° inclination, on the maxilla with a KDA0F3602 implant under oblique load in Type 2 models.

An additional model is considered as a proof for the affirmation about the thread design being the reason for the models with KDA0F3602 implants showing more critical results Figure 14 presents the behavior of stress and strain distribution at the maxilla for a Type 2 model of a squared thread implant with a Young's modulus of 110 GPa and a Poisson's ratio of 0.35 which correspond to the material properties of the V thread implant used in this study. The implant is under an oblique load of 150 N as stablished before. The results from Figure 14 and Figure 9 (c,

f) are almost identical which is enough to conclude that thread geometry is the most important factor, not even the 10 GPa difference of the Young's modulus value alters the results.

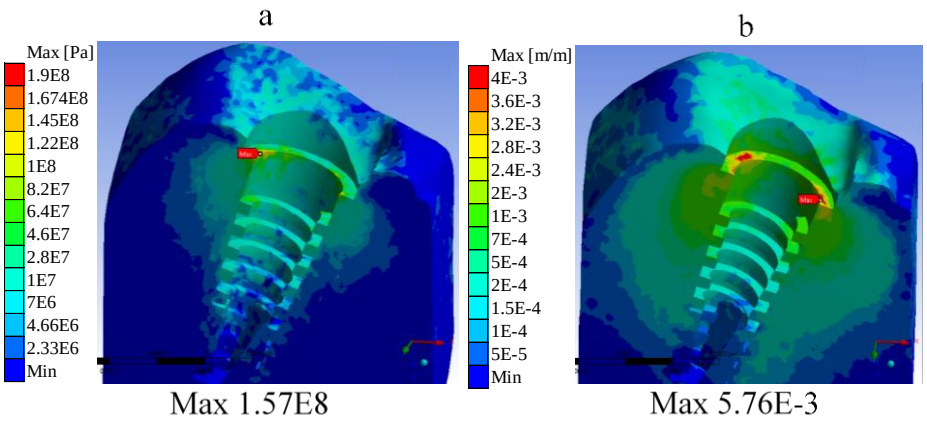

Figure 14. Von Mises (a) stress and (b) strain results for a Type 2 model with a 20° inclined TLX3409 implant with KDA0F3602 material properties under oblique load.

4.3 Comparison between isotropic and anisotropic models

In ideal isotropic models is necessary to verify the stress values for both cortical and trabecular bone because the amount of the last is bigger than in anisotropic models and it is not dispersed, it is concentrated at the center. For the least dense bone, stress should not exceed 5 MPa. Type 2, Type 3 and Type 4 models with TLX3409 implants are compared because this reference has shown better stress and strain distribution than the KDA0F3602 implants.

Figure 9 (a, d), Figure 15 and Figure 16 present the respective stress and strain results for Type 2, Type 3 and Type 4 models under the oblique load. Type 3 stress and strain results are more uniform, symmetrical and concentrated in the apex of the implant, it surpasses the limit of stress in a very limited region. On the other hand, Type 4 model presents a wider distribution of stress

on the cortical bone due to the presence of trabecular tissues at the center, it also exceeds the stress limit at the peri-implant region. Although, the transfer of the load is not continuous as in anisotropic models, the transition from cortical to trabecular bone is abrupt and after checking the less dense region, it shows a big amount of critical surface (Figure 16 b). Both Type 3 and Type 4 models are not an adequate representation of the anisotropic models which are closer to real conditions, while Type 3 behaves as if there was no load applied, Type 4 model spreads the load in an atypical way, causing more damage to the maxilla.

Due to the complexity of in vitro tests, FEM provides an accurate attempt to simulate real situations as is the case for dental implant treatments, but simplified models as Type 3 and Type 4, with isotropic nature can give misleading results.

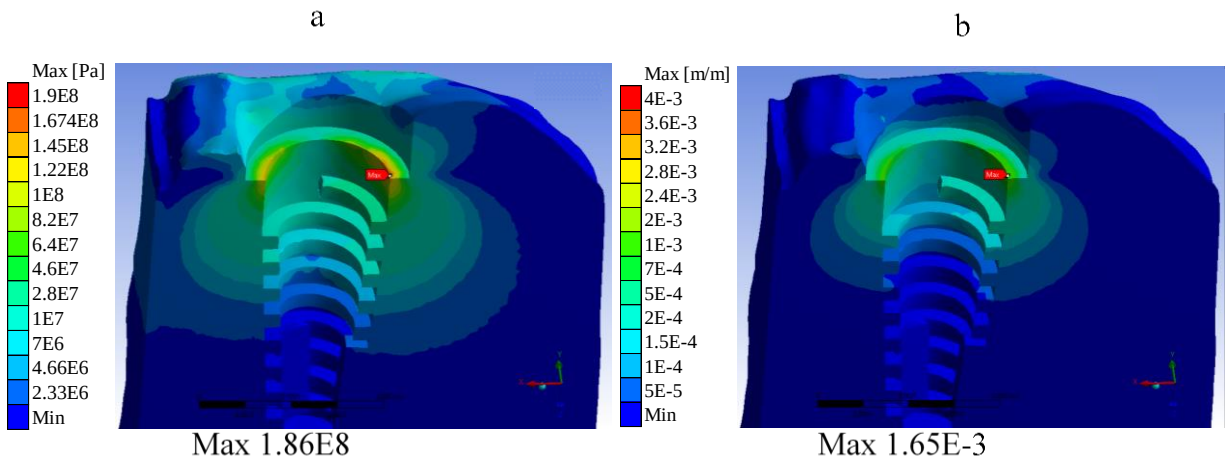

Figure 15. Von Mises (a) stress and (b) strain results for a Type 3 model with a 0° inclined TLX3409 implant under oblique load.

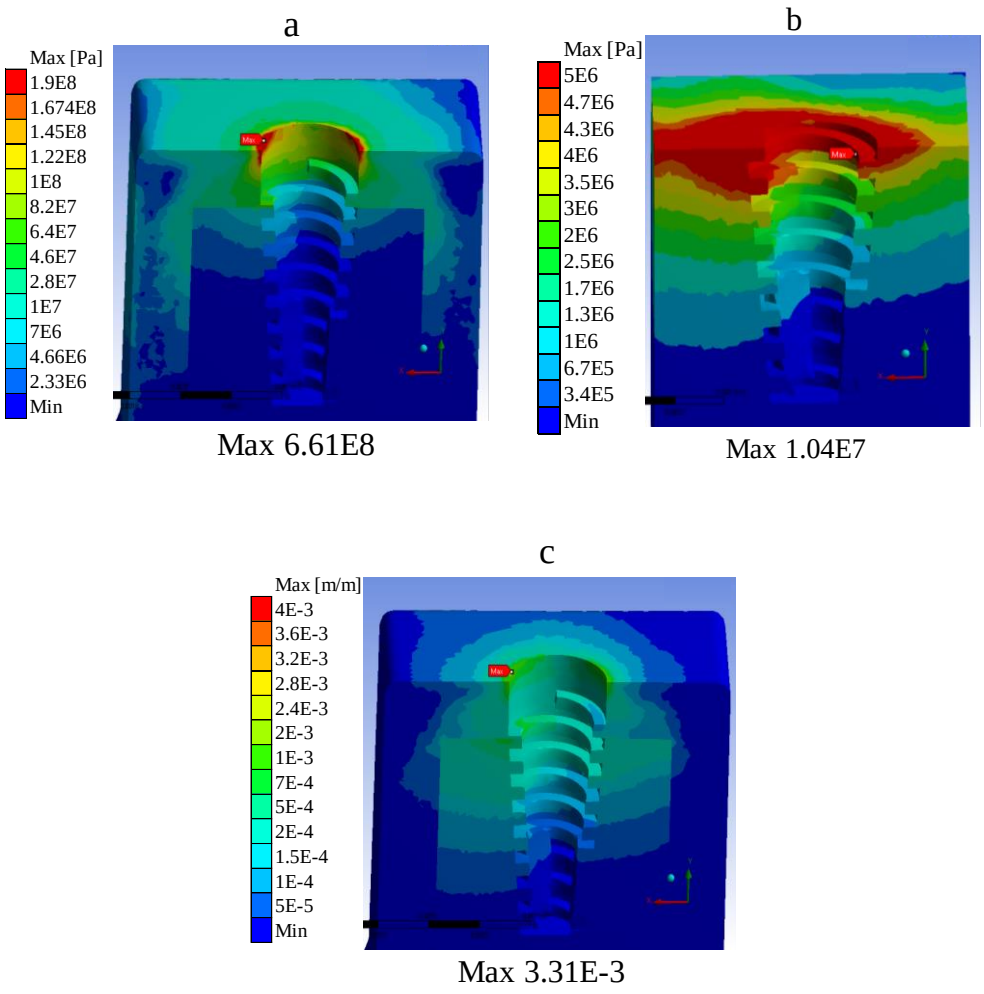

Figure 16. Von Mises stress results for a Type 4 model with a 0° inclined TLX3409 implant under oblique load in (a) cortical bone section, (b) trabecular bone section and von Mises (c) strain results in cortical and trabecular bone.

For further analysis, Table 11and Table 12 presents the results obtained for isotropic models Type 3 and Type 4 under axial and oblique load with both implant references.

Table 11.

Maximum von Mises stress and strain values in the model, indicating its location, and maximum values for the maxilla for Type 3 models with TLX3409 and KDA0F3602 implants.

Implant refenrence			TLX3409		KDA0F3602	
Inclination			0°	15°	0°	15°
Axial	Max stress [Pa]	Model	2.84E7 (A)	5.13E7 (M)	7,64E7 (M)	9,09E7 (M)
		Maxilla	2.19E7	5.13E7	7,64E7	9,09E7
	Max strain [m/m]	Model	2.04E-4 (M)	4.29E-4 (M)	1,9E-3 (I)	2,66E-3 (A)
		Maxilla	2.04E-4	4.29E-4	1,36E-3	1,25E-3
Oblique	Max stress [Pa]	Model	2.53E8 (A)	2.16E8 (A)	5,29E8 (M)	1,35E9 (M)
		Maxilla	1.86E8	1.91E8	5,29E8	1,35E9
	Max strain [m/m]	Model	1.65E-3 (M)	1.60E-3 (M)	9,37 E-3 (M)	4,55E-2 (I)
		Maxilla	1.65E-3	1.60E-3	9,37E-3	1,67E-2
Abutment (A) Implant (I) Maxilla (M)						

Table 12.

Maximum von Mises stress and strain values in the model, indicating its location, and maximum values for the maxilla for Type 4 models with TLX3409 and KDA0F3602 implants.

Implant refenrence			TLX3409		KDA0F3602	
Inclination			0°	15°	0°	15°
Axial	Max stress [Pa]	Model	6.67E7 (C)	5.64E7 (A)	3,78E7 (A)	1,28E8 (C)
		Cortical	6.67E7	4.54E7	1,78E7	1,28E8
	Max strain [m/m]	Model	2.66E-3 (A)	4.71E-4 (A)	2,52E-4 (A)	6,06E-3 (I)
		Cortical	3.38E-4	3.87E-4	1,80E-4	1,68E-3
Oblique	Max stress [Pa]	Model	6.61E8 (C)	2.55E8 (A)	2,99E8 (I)	3,85E8 (C)
		Cortical	6.61E8	1.85E8	2,01E8	3,85E8
	Max strain [m/m]	Model	2.30E-2 (A)	2.16E-3 (A)	1,83E-3 (C)	2,27E-2 (I)
		Cortical	3.31E-3	1.66E-3	1,83E-3	9,10E-3
Abutment (A) Implant (I) Cortical (C)						

Type 3 models, which are complete high density cortical bone, are the ones with the less failures for von Mises stress and strain. In the models with squared thread implants, their peaks are lower than the limits taken as a reference which indicates that bone properties are far from real

conditions because the response of it is different to anisotropic models which are closer to reality. Maximum values can be similar in some cases but the distribution of the stress and strain do not correspond to real a response, leading to wrong conclusions. A similar behavior occurs in Type 4 models, maximum values are similar in some cases to Type 1 and Type 2 models but its distribution and general response of the bone are not related, peak regions are just a portion of the maxilla, it does not represent a complete model.

5 Conclusions

Under axial load, anisotropic models with squared thread implants behave properly and do not fail by stress or strain even at inclined positions. V-shaped thread implants tend to cause strain failure, increasing with the angle of inclination.

Uneven distributions of von Mises stress and strain in models with inclined implants is due to the direction of the force producing high bending moments which yield higher stress values.

The differences between the von Mises stress and strain response for the 15° and 20° inclined implant models are not conclusive regarding the 5° angle variation. Some of the models with KDA0F3602 implant present a more noticeable zone of failure despite of their similar maximum values, meanwhile in the models with TLX3409 implant, the size of the critical zone and maximum values are similar. Trying lower and higher values for the inclination of the implant is recommended for future studies as an attempt to clarify the influences of the angle.

The length of the implant is not relevant in the stress distribution, as Baggi *et al.*, (2008) and other studies have corroborated. Minimum diameter and material properties variation of the implant do not affect how the bone performs under oblique loads. Moreover, thread design is a key factor and the responsible for the success or failure of a dental implant FEM study.

Anisotropic models without cylinder resist better due to the denser cortical bone in the peri-implant region. The simulation of the new bone tissues represented as the isotropic cylinder (E=6GPa) support less load and distributes the stress and strain in a way that causes more critical conditions. Based on the results is fair to say that the recommendation made by specialists about avoiding too much time before seeking a dental implant treatment is correct. After a long time exposure without teeth, the bone reabsorbs and it would be necessary to use bone allografts which may end in a failure. If allografts were used as in Type 1 models, is suggested to simulate more accurate models because isotropic or even anisotropic (Type 2) models do not relate to these cases behavior.

For dental implant treatments where is not possible to locate the implant in a vertical way, thus an inclined position is needed, squared thread implants are better than V-shaped ones because the load is better distributed, minimizing strain concentration on the bone.

Ideal isotropic models based on the Type II bone classification by Zarb & Lekholm (1985) or even more simplified models, fail to represent the behavior of the bone under critical loads in anisotropic models which are closer to real life conditions. For inclined TLX3409 implant models, isotropic bone supports an oblique load of 150N, while for anisotropic bone models the maximum load allowed is around 70N in order to avoid critical strain values.

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