

Article

Finite Element Analysis (FEA) of the Stress and Strain Distribution in Cone-Morse Implant–Abutment Connection Implants Placed Equicrestally and Subcrestally

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Abstract: Peri-implant bone resorption has been reported around some implants after loading, which could create problems for the peri-implant soft and hard tissues’ long-term stability. The reasons for this are still not known. However, relevant importance could be given to this due to the presence of a bacterial contamination at the micro-gap level between implant and abutment. In this regard, external and internal implant–abutment assemblies have been shown to be much more permeable to bacterial colonization than Cone-Morse or conical connections. The placement of a subcrestal implant could have aesthetic advantages, therefore allowing a better prosthetic emergence profile. In literature, controversial experimental and clinical results have been reported on bone resorption around implants placed equicrestally and subcrestally. Interestingly, Finite Element Analysis (FEA) studies revealed to be extremely useful for assessing the peri-implant bone strain and stress. Thus, this study conducted a FEA evaluation of implants with a Cone-Morse implant–abutment assembly inserted into a bone block model mimicking equicrestal (0 mm) and subcrestal placements (−1 and −2 mm). Results demonstrated that maximum stresses were observed in the cortical bone around equicrestally placed implants, with the lowest in the 2 mm subcrestally placed implant and intermediate stresses within the 1 mm subcrestally placed implant. The cortical bone resulted more stressed under lateral loads than axial loads. In conclusion, this FEA study suggested a subcrestal implant placement ranging between −1 and −2 mm to obtain an adequate peri-implant stress pattern.

Keywords: bacterial leakage; Cone-Morse connection; dental implants; equicrestal implant placement; finite element analysis (FEA); implant–abutment junction; implant placement; stress distribution; subcrestal implant placement

1. Introduction

The peri-implant bone and soft tissues preservation over the long-term is extremely important for the implant success rate [1]. However, in some cases, it is possible to

observe a resorption of the bone. The causes of this are not yet completely known, but are in all probability related to a multitude of different factors, i.e., reformation of the biological width, presence of a bacterial infiltration at the implant–abutment micro-gap level, implant overloading, peri-implantitis, relative micromovements, peri-implant bone density, peri-implant soft tissue phenotype, surgical trauma during implant insertion, inter-implant distance, surface structure, and implant neck or abutment characteristics and macro-design [2–10]. A relevant role is certainly held by the presence of a bacterial reservoir at the level of the voids present in the implant–abutment junction (IAJ) after the insertion of the abutment into the implant [9–11]. Furthermore, in the literature, it is known that not all implant–abutment connections behave in a similar way. For example, external and internal implant–abutment assemblies have been shown to be much more permeable to bacterial colonization than Cone-Morse or conical connection assemblies [11,12]. In fact, the conical contact between the implant and the abutment has been demonstrated to allow a better distribution of masticatory forces and a reduction of mechanical stress on the surrounding bone. This is especially important to promote bone health and prevent its resorption. In addition, factors such as the type of load considered and bone quality play a role both on primary stability, but above all, in preventing bone resorption. In addition, the collar area of the implant plays a crucial role as it reaches higher stress values than the apical area. Alternatively, the crestal and subcrestal placement of dental implants refers to the depth at which the implant is inserted into the bone tissue of the jaw. Crestal positioning is the most common technique, in which the implant is inserted in the site of tooth extraction or in a previously edentulous area, until it reaches the level of the alveolar bone margin. In this way, the neck of the implant is at the same level of the gum or slightly below it. This technique is commonly used when the level of the alveolar bone is adequate enough to ensure a good primary stability of the implant and a correct aesthetics for the final result. On the other hand, subcrestal implant placement involves inserting the implant so that the implant neck is positioned below the level of the alveolar bone margin. This can be done when the quantity of the alveolar bone is insufficient in height or thickness [5–7]. The goal is to cover the implant neck with the gum tissue, creating a “shield” effect that can contribute to the long-term stability of the implant and the preservation of gingival aesthetics. Both methods present some advantages and disadvantages. The crestal positioning could offer greater surgical ease and better accessibility for cleaning or maintenance of the implant. However, it may require an adequate volume of alveolar bone to achieve a sufficient primary stability. Subcrestal implant placement could prove to be useful in cases where bone volume is reduced or in order to improve gingival aesthetics, but the surgical procedure may become more intricate and necessitate heightened focus on gum management during the healing process [5,8]. The choice of where to position the implant will depend on various factors, including the patient’s anatomical features, desired aesthetics, bone stability, and implant surgeon preferences. Inserting an external or internal connection below the alveolar crest would mean to apically move the micro-gap colonized by bacteria with a possible resultant higher resorption rate [12]. On the contrary, those connections which are more resistant to the bacterial leakage, e.g., Cone-Morse and conical ones, could be positioned more apically in relation to the alveolar crest with a very small or no peri-implant bone resorption [13–15]. Thus, the subcrestal positioning of a Cone-Morse connection could be possible from biological and clinical points of view [13–15]. This practice could carry significant beneficial implications, mainly from an aesthetic point of view, because it would allow a better prosthetic emergence profile. However, different and controversial results have been reported in the literature by *in vitro*, animal, and clinical studies, as well as systematic reviews of the literature, about different resorption rates related to implants inserted in equicrestal or subcrestal positions [16–32].

In recent years, Finite Element Analysis (FEA) studies demonstrated to be extremely useful in evaluating several different aspects of the biomechanical characteristics of dental implants and bone [33,34]. FEA analysis is a computational simulation technique that uses numerical methods to model and analyze the behavior of an object or structure under

load. In case of dental implants, an FEA model can be created to represent the implant, surrounding bone, and gum tissue. The model can be used to simulate loading conditions to which the implant is subjected during chewing and to evaluate the stress and deformation factors generated into the bone and within the implant itself. The Finite Element Method (FEM) can also be used to study the behavior of dental implants based on the depth of dental insertion into the bone tissue and is also able to provide information about the load distribution between the implant and the surrounding bone at different insertion depths. This may help identifying areas of increased strain or overload that could affect the stability and durability of the system [35–40]. Furthermore, FEA studies could help assess how insertion depth affects the primary stability of the implant, thereby identifying the ideal depth for achieving the optimal implant anchorage in bone tissue, since primary stability is considered a critical factor for successful bone integration. In this context, the FEA could also estimate the surrounding bone response to the implant insertion at different depths. This may provide simulated indications of possible bone resorption or increase in bone density, which may occur over time due to the interaction between implant and bone [40–42].

This information is important to ensure that neither the implant nor the bone would be subjected to excessive stresses that could lead to implant failure or complications. It is important to note that FEA is a numerical simulation tool, and its predictions depend on the accuracy of data and material properties used in the model. Therefore, FEA studies should be considered as a support for the interpretation of the results and further clinical decisions should be made basing on an overall assessment, also taking into account other patient-specific clinical and radiographic considerations [33–42].

For that reason, this study has been conducted to perform a FEA survey of implants presenting a Cone-Morse implant–abutment assembly, inserted in different positions relative to the alveolar crest. The hypothesis that is carried out is related to the non-dependence of bone thickness with the depth of insertion of the implant.

2. Materials and Methods

2.1. Modelling

A cross-section of a bone block with a width of 10 mm and a vertical height of 17.5 mm was designed with a computer-aided design (CAD) software (Autodesk Inventor, San Francisco, CA, USA) based on a computed tomography (CT) scan of a patient, which modelled the correct geometries. The cortical area resulted to be 1.5 mm in thickness (Figure 1a). The implant model used had a diameter of 4 mm and a length of 9 mm, while the abutment had a length of 8.3 mm and the same diameter (Implacil De Bortoli, São Paulo, Brazil). The fillets depth was 0.4 mm. In Figure 1b, it is possible to observe both the drawing and dissected views, in which the Cone-Morse connection between implant and abutment is represented.

The implant model has been equicrestally placed in the bone block so that the implant shoulder was at the same level of the crest. On the contrary, subcrestal patterns have been generated by the placement of the implant model at 1 mm and 2 mm below the crestal level, respectively (Figure 2). The software used to perform these placements was Ansys Workbench (Canonsburg, PA, USA).

It is common practice to consider both cortical and trabecular bones as isotropic materials when utilizing a FEA study model to examine the behavior of bones in relation to dental implants. This would mean that the mechanical properties of the bone have been assumed to be uniform and not influenced by a specific direction [1]. The cortical bone is the outermost and most compact region of the bone, forming a protective layer around the inner trabecular bone. Instead, the trabecular bone, also known as spongy bone or cancellous bone, is a porous framework composed of bony trabeculae creating a three-dimensional network [2]. In the context of a FEA model, cortical bone is represented as a more rigid and stronger material, while trabecular bone is considered more flexible and less resistant. This difference in mechanical properties reflects the physical characteristics

of the bone itself. When developing an FEA model to simulate cortical and trabecular bone, specific values of Young's modulus (stiffness measurement) and Poisson's modulus (deformability measurement) can be assigned to both bone types. However, it is important to note that parameter values can greatly vary depending on the anatomical location and individual variabilities. In addition, the mechanical characteristics are also dependent on density. Hence, chronic diseases or even aging can lead to a change in the density value that might compromise results. In this study, bone density belonging to category D3 according to the Misch classification was taken into account. It is possible to acquire the mechanical properties related to cortical and trabecular bones from biomechanical studies, experimental data, or scientific literature. Typical Young's modulus values for cortical bone can range from 13 to 20 GPa, while for trabecular bone the range is from 0.1 to 4 GPa. Conversely, Poisson's modulus for both types of bone can be considered around 0.3 [1–3]. Representing cortical and trabecular bone as isotropic materials could allow the simplification of modelling and analysis within FEA study; however, it is important to emphasize the complex biological nature of the bone and that its structure and mechanical properties could vary even within the same individual.

The dimensions and properties assigned to the models related to the cortical bone, trabecular bone, and titanium implant used in this study are reported in Table 1.

Table 1. Properties of materials used for this Finite Element Analysis (FEA) study.

Material	Young's Modulus (GPa)	Poisson's Ratio
Cortical bone	13.7	0.30
Cancellous bone	0.3	0.30
Titanium	117	0.30

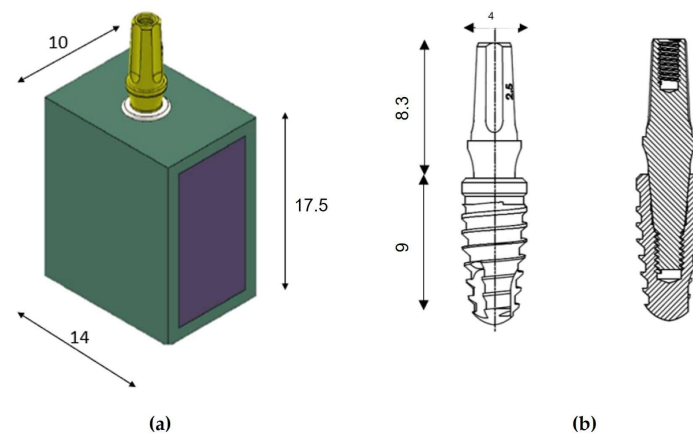


Figure 1. (a) Dimensions of the model used; (b) Implant and abutment sizes. All dimensions are expressed in mm.

2.2. Loads

Among the most important finite element parameters, in addition to bone properties, are loading and boundary conditions. In this study, limiting conditions have been established, corresponding to the mesial and distal surfaces of the bone model. Afterwards, boundary contact conditions between implant and trabecular bone were fixed simulating an ideal osseointegration. The simulated load has been applied on the upper surface of the abutment with an oblique force of 200 N of magnitude and with an inclination of 45° with respect to the longitudinal axis of the implant (Figure 3).

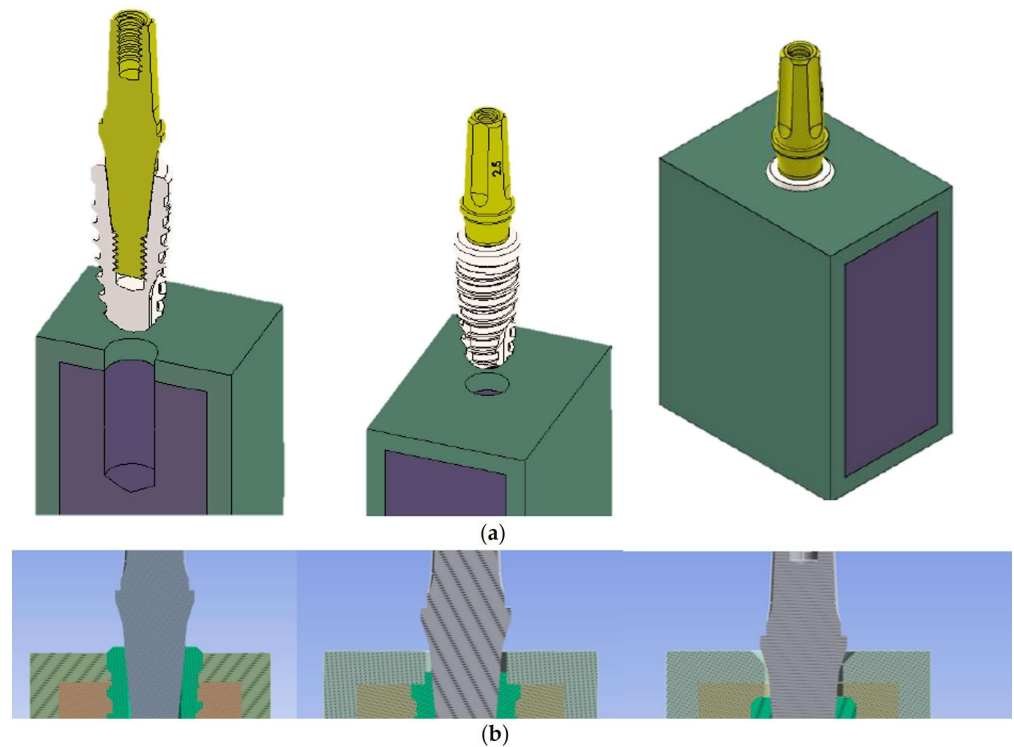


Figure 2. (a) Modelling of the three components: bone (cortical in green and cancellous in violet), screw (in white), and abutment (in yellow) using Autodesk Inventor (San Francisco, CA, USA); (b) Insertion of the equicrestal (0 mm) and subcrestal (−1 mm and −2 mm) implants (the abutment in grey and the screw in green) into the bone (cortical in light green and cancellous in brown) using Ansys Workbench (Canonsburg, PA, USA).

Load: 200 N

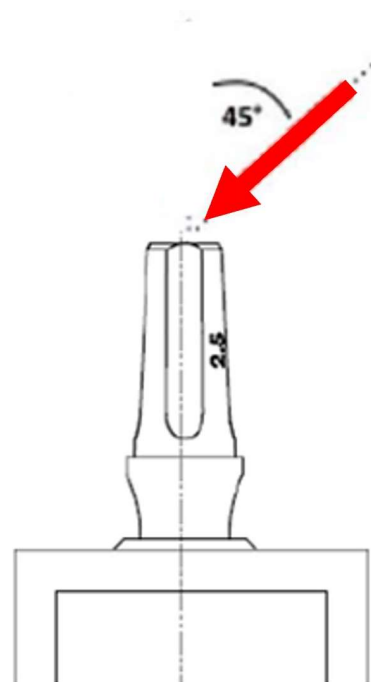


Figure 3. Loading force of 200 N of magnitude and 45° of inclination applied on the abutment.

2.3. Finite Element Method (FEM)

The accuracy of results proved to be strongly dependent on the convergence testing process and the mesh quality [33–35]; thus, the mesh element size chosen for this research was established at 0.5 mm of tetrahedral elements in the part of the screw and bone. Contrarily, on the lower surface of the abutment, a mesh refinement was performed in order to achieve a more accurate distribution of Von Mises stress. This area is considered critical when the implant is subjected to inclined loads, as supported by existing literature [35]. Mesh refinement can be useful in solving problems that require more precise details of the model or involve high stress gradients, such as analyzing complex structural components or simulating fluid flows. However, it is important to note that excessive mesh refinement can lead to longer computation times and increased complexity in managing the results. Therefore, it is essential to balance the mesh refinement based on the problem specifications and available computational resources to obtain reliable and efficient results. In this case, a mesh refinement was applied, resulting in a reduction of the element size to 0.3 mm in the abutment portion (Figure 4).

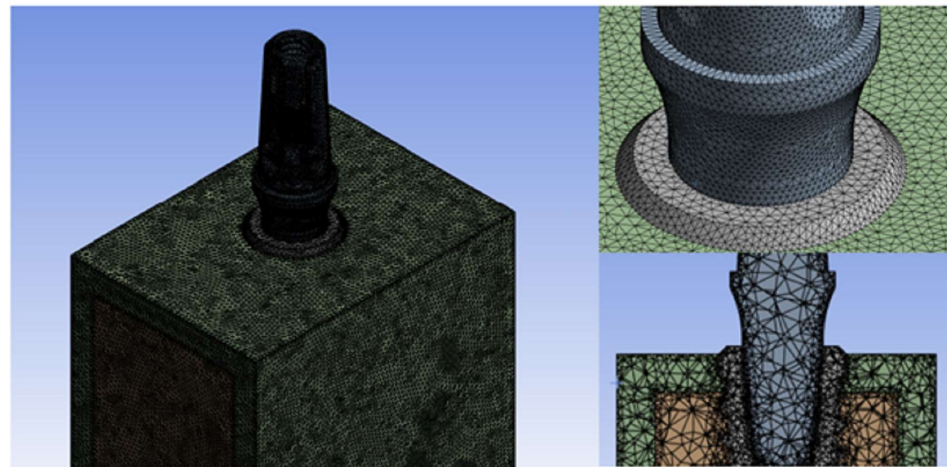


Figure 4. Mesh size: 0.5 mm and 0.3 mm.

The friction generated between the abutment and the dental implant is an important factor to consider when designing and installing a dental implant. Indeed, the final goal is obtaining adequate stability and tightness between the abutment and the implant, in order to guarantee the absence of micromovements at the implant–abutment connection zone and a long-term implant stability. An appropriate level of friction between the abutment and the implant is desirable to avoid those micro-movements that could compromise the integrity of the interface, prevent the loss of the prosthetic material and the abutment mobility, as well as reduce the risk of bacterial infiltration by creating a suitable bacterial seal. A frictional coefficient of 0.3 was set as the implant–abutment contact condition in the present FEA study (Figure 5). Between the implant and the bone, on the other hand, a fixed type of contact was considered, without any type of micromovement. This hypothesis is validated from the moment in which the osseointegration between the two surfaces occurs. The software used for the FEA simulation was Ansys Workbench (Canonsburg, PA, USA). The application of FEA to dental implants raises important ethical considerations related to scientific validity, informed consent, respect for the limits of the method sharing of results, and benefit to patients.

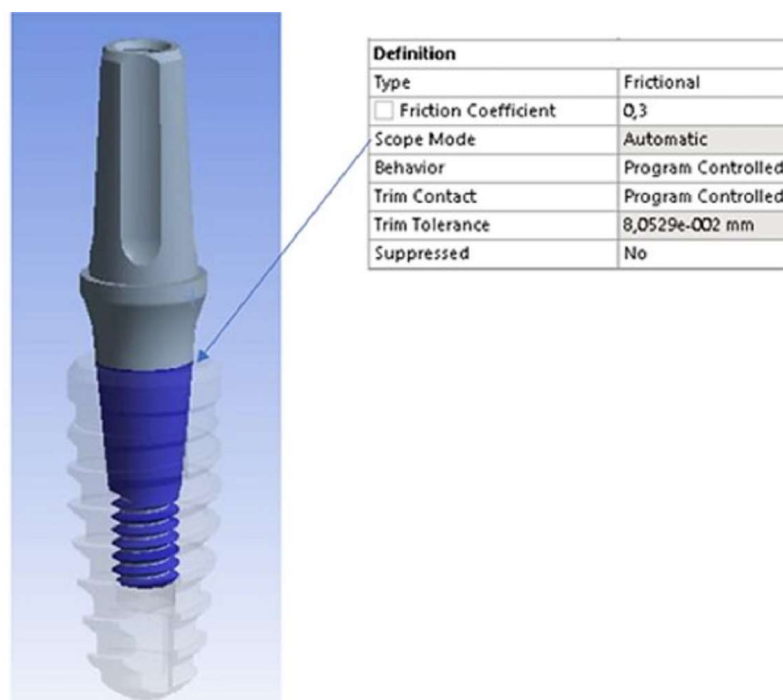


Figure 5. The implant–abutment contact condition set at 0.3 as frictional coefficient.

3. Results

Data concerning mathematical solutions have been converted into visual results as color gradients range from red to blue. The blue color indicated the minimum stress, whereas the red one the maximum stress. All the shades present in this range were considered as the stress variation. Subsequently, stress values were measured at different points collected from the studied models and then compared. Von Mises equivalent stress levels were used to identify points with the greatest stress for both dental implants and bone [42]. Figure 6 shows results of Von Mises stresses on both cortical and trabecular bones and on implants.

Von Mises stresses displayed in Figure 6 at various depths of implant positioning show how the stress was higher in case of implant positioning at the same level of the bone (equicrestally). In addition, it was detected higher stresses in the cortical bone than in the trabecular bone due to the different stiffness of materials. In particular, in the equicrestal positioning, it can be observed how the first four fillets of the thread recorded stresses ranging between 80 and 170 MPa, while the latest fillets recorded stress values ranging from 3 MPa to 30 MPa.

In the apical area of the implant, it can be observed how the equicrestal positioning induced a compressive stress on the surrounding bone, reaching a stress level of approximately 50 MPa. However, this value did not compromise the strength of the trabecular bone, as the compressive strength of the trabecular bone relies on both its density and unique structure, and it is precisely this structure that gives it a greater resilience than the cortical bone that is more compact. On the other hand, the maximum trabecular bone stresses were registered close to the implant head, and they linearly decreased with the decrease of bone depth. Indeed, stresses on the cortical and trabecular bones increased when the thickness of the cortical bone decreased.

The applied oblique loading caused higher Von Mises stress values on both cortical and trabecular bones. After the evaluation of stresses in the bone around the equicrestally and -1 mm and -2 mm subcrestally placed implants, three different situations could be observed: the highest stress could be recorded within the cortical bone around the equicrestally inserted implant, the intermediate stress around the subcrestal implant placed

at -1 mm, and the lowest one was detected in the subcrestal implant placed at -2 mm (Figures 6 and 7).

Figure 7 demonstrates that as soon as implants further penetrated the jaw, stresses in the cortical bone decreased, whereas stresses in the trabecular bone increased. The maximum stresses found in the cortical bone decreased from 60 to 20 MPa, while in the trabecular bone, the region experiencing stresses greater than 8 Mpa expanded up to three threads of the implant screw. However, from the results, it was possible to notice how under eccentric load the subcrestal implant positioning was able to transfer a compression stress from the cortical bone to the trabecular bone in a more uniform manner.

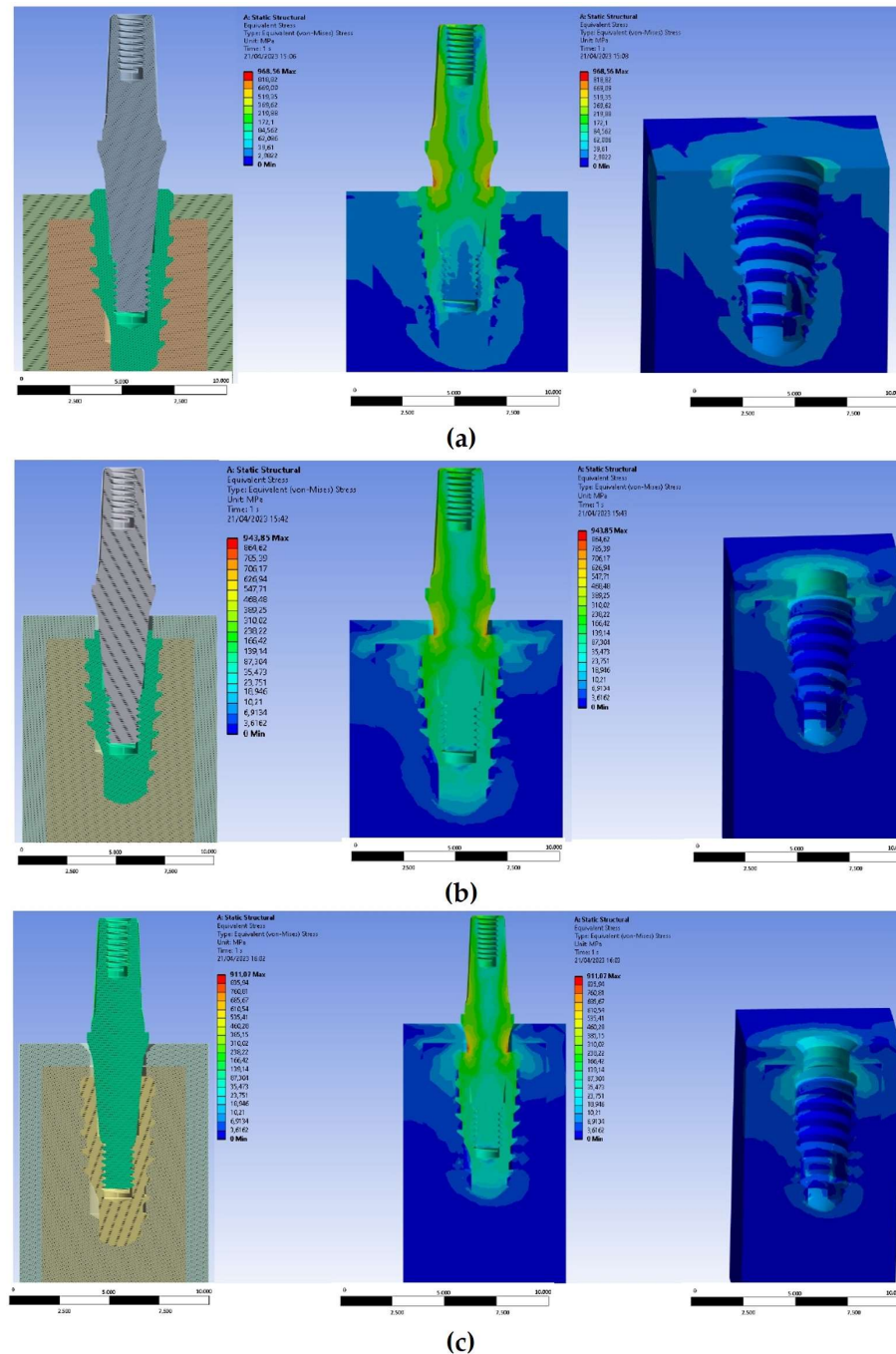


Figure 6. Von Mises stresses in the three analyzed implant models: (a) equicrestally, (b) subcrestally (-1 mm), and (c) subcrestally (-2 mm) positioned.

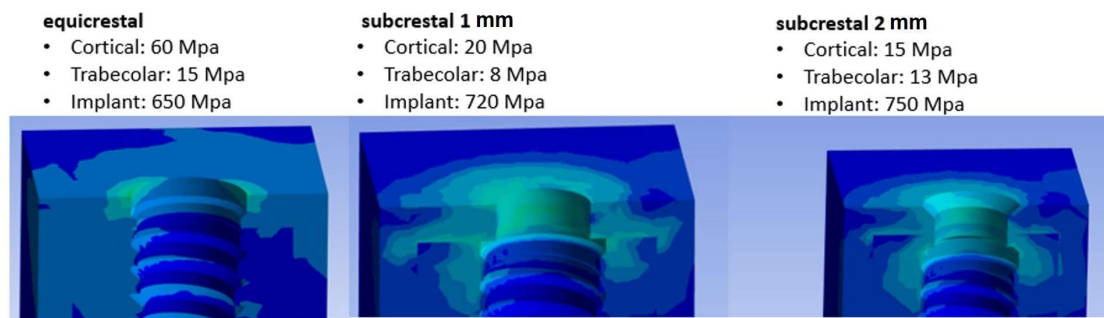


Figure 7. Comparisons of stresses detected within the bone around equicrestally and 1 mm and 2 mm subcrestally placed implants.

4. Discussion

As it has been already reported in the literature, the insertion of an implant platform in a more apical position relative to the alveolar crest could give better aesthetic results [13,14]. However, only implants that presented a very low percentage of bacteria at the IAJ level could be safely inserted in a subcrestal position [43–48]. Different experimental, clinical, and radiological results have been reported when Cone-Morse implants were inserted in a subcrestal position; however, a consensus on this topic has been never reached [18,20,25,27,28,32]. In animal experiments and in human histological studies on retrieved Cone-Morse implants, it was found that no resorption or a smaller amount of resorption of the peri-implant bone was present, and also that, in some specimens, newly formed bone tended to overgrow the implant shoulder and the micro-gap, touching the abutment surface [13,14,21,30,43–46]. Overall, a systematic review with meta-analysis reported that in most of the evaluated papers no differences were found in peri-crestal bone levels of equicrestally and subcrestally situated implants [24]. In addition, clinical reports corroborated these data with similar results [22,23]. Other FEA studies have also found a significantly greater strain peak in external hexagon connections when compared to Cone-Morse connections [39,40]. Moreover, it was also reported that peak stresses were moved away from the crestal peri-implant bone to subcrestally positioned implants [7,16].

The cortical bone is responsible for transmitting occlusal loads to the implant bone interface, due to its high stiffness compared to the trabecular bone. For this reason, implants inserted in a subcrestal position that do not have contact with the cortical bone exhibit distinct mechanical characteristics compared to those placed in a more crestal position. It has been observed that the maximum compression stress value on the bone provides useful information to analyze bone resorption with respect to the tension stress value [10]. In particular, Salles Sotto-Maior et al. [19] provided evidence of bone resorption resulting from stress overload when compression stress exceeds the range of 80–130 MPa on the cortical bone. In contrast, the present study found that an equicrestal implant positioning, coupled with the application of an oblique load, resulted in a stress level of 60 MPa on the cortical bone. However, when using subcrestal placements, significantly lower and safer stress values of 20 and 15 MPa were observed. Consequently, this reduction in stress can be attributed to the placement of the implant at a depth of approximately 1.5 mm, leading to the growth of coronal bone at the interface and contributing to an increased success rate. In the present FEA study, it was observed that as the depth of implant placement increased, there was a corresponding rise in compressive stress on the apical region of the implant, as shown in Figure 7. This occurrence can be attributed to the displacement of the fulcrum of force towards the apical region, resulting in a greater lever arm. This displacement is caused by the increased interaction between the implant and trabecular bone, leading to the observed phenomenon. In addition, the reduced section of the apical area of the implant decreased the contact area available to dissipate stress with the bone, and therefore, there is an increase in stress. These observations provide a potential explanation for the

critical significance of the system design, particularly in the apical area, when choosing the subcrestal implant positioning.

To ensure appropriate implant placement, it is crucial to carefully assess occlusal loads. Therefore, conducting these evaluations prior to any occlusal adjustments is imperative in order to mitigate the risk of bone resorption resulting from elevated stress levels. In both 1 mm and 2 mm subcrestal models, a reduction in stress was observed in the cortical area. This finding suggests that, in scenarios where patients are subjected to occlusal loads, such as parafunctions, a subcrestal positioning would be more advantageous compared to an equicrestal positioning. This analysis allowed us to understand the factors that must be considered when choosing the depth of insertion of the implant. It is important to highlight that subcrestal placement stresses a significant portion of the trabecular bone, aligning with the findings of Rismanchian et al. [37]. This supports the notion that appropriately stimulated bone can undergo reshaping along the implant surface. The FEM analysis helped these researchers in understanding that when implant positioning occurred subcrestally at about 1 mm, the transfer of load was more beneficial for bone growth when compared to cases where the insertion depth was greater. The reason can be linked to the fact that in this latter scenario, a higher amount of tension was absorbed, resulting in a notable reduction of tension within the trabecular bone, which did not favor new bone formation.

FEM analysis is a powerful simulation tool that allows you to evaluate structural behavior and stresses in a variety of situations [48,49]. However, like any modelling and simulation tool, there are some limitations that are important to consider when using FEA to assess stress variations. Among them, we find the accuracy of the input data. In fact, the accuracy of FEM analysis results depends on the quality of the input data used, such as loading conditions and material properties. With respect to this last point, all materials were considered homogeneous, isotropic, and linearly elastic, although the mandibular cortical bone was crosswise isotropic and inhomogeneous. Alternatively, considering the materials as anisotropic, with mechanical properties that vary in different directions, they would require the use of more sophisticated and complex FEA models and the consideration of additional parameters to describe and determine the mechanical behavior of the material. Therefore, simplifying a material as isotropic can be an approximation and may not fully reflect the actual behavior of the material. In general, the choice to consider a material as isotropic or anisotropic depends on the specific characteristics of the material and application, as well as the objective of the FEA analysis. It is important to carefully consider which approach is most appropriate to obtain accurate and representative results. However, it also holds significance to take into account the morphology, density, and concentration of the trabeculae, in order to determine their influence on the results obtained from FEA simulations. In addition, simplifications have also been made with regard to geometry. These simplifications may affect the final results and may not consider all the real interactions between components. Despite this, for the purpose of simplification, these properties were disregarded in the modelling of this study.

Other two identified factors that influenced the simulation were the material used for the implant and the surface roughness. The optimal properties of the implant material allow for increase in the bone regeneration process and, hence, the early stabilization of the implant [48,49]. Instead, the increased roughness of the surface in turn increased the coefficient of friction between the surface of the material [50]. In this FEA study, details of the implant surface roughness have been ignored since the study aim focused only on the effect of tensions within the bone.

Although FEA studies have been previously employed to anticipate the biomechanical performance of different implant designs and examine the impact of clinical factors on the success of implants, there is still a need to comprehensively assess and understand the correlation between numerous variables for long-term implant success, aiming to enhance clinical results. These variables encompass refining the simulation process with realistic properties of materials and their geometry, accounting for variations of the bone porosity, considering design parameters, implant surface roughness, different analysis techniques,

variations in insertion conditions, and the possibility to incorporate cyclic loads that may induce implant fatigue.

Last but not least, it is important to consider that although this FEA study provides useful results to lay the foundations for establishing correlations with clinical data, it still has limitations. Indeed, according to Misch's theory, it should be considered that bone density plays a fundamental role in the definition of mechanical behavior and that factors such as disease, age, smoking, or cases of bone degeneration can compromise the ideal behavior of the bone as described in this study. This research has been essential in refuting the null hypothesis stated in the Introduction section, as it has demonstrated the crucial role of implant positioning and bone crest thickness in influencing the osseointegration process [51].

5. Conclusions

In this study, higher stresses were recorded in the cortical bone. However, this should not represent a risk element as it has been expected because the cortical bone had a higher modulus of elasticity than the trabecular bone. However, a complete insertion of the implant into the trabecular bone could lead to complications due to the higher generated stresses. Another factor to keep in mind is the apical area of the implant that, as we have seen, increases the trabecular bone with compression, and this increase has a plateau at about 1.5 mm, and then, it increases with the depth of insertion of the implant.

In conclusion, it can be observed from the results obtained by the subcrestally positioned implants that a reduction in bone stress and strain in the surrounding area is noticeable only at specific insertion depths: -1 mm or -2 mm. Thus, implant positioning at 1.5 mm may be recommended to obtain an adequate stress distribution pattern. Conducting specific studies on real cases in the future could help clinicians understand the depth of implant insertion.

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