International Journal for Multiscale Computational Engineering, 20(4):43–56 (2022)

BIOMECHANICAL EVALUATION OF MARGINAL BONE LOSS IN THE SURROUNDING BONE UNDER DIFFERENT LOADING: 3D FINITE ELEMENT ANALYSIS STUDY

Abdelhak Ouldyerou,[1] Ali Merdji,[1,2] Laid Aminallah,[1] Velaphi Msomi,[3] Perk Lin Chong,[4] & Sandipan Roy[5,*]

[1]*Faculty of Science and Technology, Department of Mechanical Engineering, University of Mascara, Algeria*

[2]*Laboratory of Mechanics Physics of Materials (LMPM), Faculty of Technology, Djillali Liabes University, Sidi Bel-Abbes 22000, Algeria*

[3]*Cape Peninsula University of Technology, Faculty of Engineering and the Built Environment, P.O. Box 1906, Bellville 7535, South Africa*

[4]*School of Computing, Engineering, and Digital Technologies, Teesside University, Middlesbrough, TS1 3BX, United Kingdom*

[5]*Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai 603203, India*

*Address all correspondence to: Sandipan Roy, Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai 603203, India, E-mail: sandipan888roy@gmail.com

Original Manuscript Submitted: 3/20/2022; Final Draft Received: 4/2/2022

Marginal bone loss (MBL) remains a controversial issue and a major complication in the field of oral and bone health. The goal of this study was to evaluate the biomechanical effect of implant length, MBL levels, and load magnitude under axial and buccolingual loading on stress at the bone–implant interface. Four case models (without bone loss, 0.5 mm bone loss, 1 mm bone loss, and 1.5 mm bone loss) and two implants with different lengths (Type A with 12 mm and Type B with 15 mm) were created using SOLIDWORKS. In the first part, an axial load of 100 N and a buccolingual load of 50 N were applied separately on the occlusal face of the crown. In the second part, different loading magnitudes (100 N, 150 N, 200 N, 250 N) were applied separately with implant A. Simulation results show that the stresses were higher with implant B in cortical bone compared to implant A, and as the bone loss increases, the von Mises stress and displacement in the bone increases in all cases. The stresses were higher in buccolingual loading compared to axial loading, and a higher magnitude of different loading generates higher stresses in the bone tissue. Through this study, it was concluded that progressive MBL and excessive loading produce higher stresses in the bone tissue, which may affect the bone remodeling process.

KEY WORDS: *dental implant, marginal bone loss, stress, FE analysis, overload*

1. INTRODUCTION

Today, dental implants are increasingly used to replace missing teeth, especially with the adoption of current technologies such as additive manufacturing (3D printing) (Revilla-León et al., 2020). Despite the success of the implantation process, many complications can occur, including marginal bone loss (MBL). Researchers in implant dentistry have used cone-beam computed tomography to determine the bone geometry before and after implantation. Their studies report radiographic MBL during and after the first year of the implantation (Saravi et al., 2020), bone loss around 1.5 mm during the first year and 0.2 mm every subsequent year (Duan et al., 2017), and the majority of implant failures happened within the first few years of implantation (Chrcanovic et al., 2018).

MBL is still a controversial issue, and many factors may influence it. According to the current literature, the following variables are primarily responsible for bone loss: implant-abutment connection type; implant position (Mailoa et al., 2015); density and quality of the bone (Ayranci et al., 2017; Taharou et al., 2021); implant stiffness and porosity (Mehboob et al., 2021); and implant geometry (Kowalski et al., 2021) such as the difference of the shape (conical, cylindrical) (Ramos and Mesnard, 2019; Didier et al., 2020), diameter (Anitua et al., 2021), neck configurations (Zhang and Yue, 2021; Ausiello et al., 2021), and thread designs (Ormianer et al., 2016; Alemayehu and Jeng, 2021). Researchers also have found that overloading and smoking contribute to marginal peri-implant bone loss (Albrektsson et al., 2019a; Naveau et al., 2019; Sadowsky, 2019; Clementini et al., 2014; Chrcanovic et al., 2015). In addition, placing two adjacent implants can also cause significant bone loss (Ramanauskaite et al., 2018), which explains why the number of implants is often limited by alveolar bone resorption. Srinivasan et al. (2017) report that severe MBL occurs when people get older. Moreover, the immunological and inflammatory reactions of the individual host immune system influence the MBL progression (Albrektsson et al., 2019b). Recently, a study has shown that an implant with a micro-threaded neck form and a rough surface can enhance the preservation of crestal bone (Al-Thobity et al., 2017). Currently, many procedures have been proposed to improve implant stability and prevent MBL such as using bone grafts and platelet concentrates (Qu et al., 2021; González-Serrano et al., 2021).

The stress analysis of the bone-implant interface has been the subject of multiple studies using finite element analysis (FEA) (Drai et al., 2018; Reddy et al., 2019; Ouldyerou et al., 2022; Kasani et al., 2019; Ali et al., 2013; Merdji et al., 2012; Korkmaz and Kul, 2021). Some of these researchers studied the distribution of stress at the level of the bone and the implant in the case of MBL. Gupta et al. (2021) numerically analyzed the effect of vertical bone loss levels in a dental implant with different diameters with one common length of 11.5 mm. They found that implant diameter profoundly affected the stresses generated in cortical bone, and the stresses in the trabecular bone were found to increase as more bone was lost. Linetskiy et al. (2017) elaborated on the effect of annual bone loss levels in different bone qualities with three different implants. They reported that for all bone types, the von Mises stresses in cortical bone decrease with an increase in the diameter of the implant. Bing et al. (2020) investigated stress distribution of the peri-implant bone resorption in three implants with different diameters by using 3D FEA. The results they obtained show that as bone resorption increased, the von Mises stress in the implant body became more significant, especially in the small diameter of the implants. Lemos et al. (2021) studied the impact of bone quality and vertical bone loss level around two implants with different implant-abutment connections (internal and external). The results showed that vertical bone loss produce higher stress and microstrain in the bone tissue, especially in the osteoporotic bone under oblique loading, and the internal connection implants showed lower stress in the cortical bone. Yoon et al. (2011) analyzed stress distributions for an osseointegrated implant after different vertical bone loss levels. They found that the stresses increased as the bone resorption level increased. Wolff et al. (2014) analyzed the influence of four different implant geometries and bone configurations on the strain patterns in the adjacent bone tissue. They found that strain is higher in surrounding bone when progressive bone loss occurs. Ercal et al. (2021) explored the influence of crown-to-implant ratio prosthetic materials and bone resorption on stress distribution of short implants. They obtained that the crown material does not affect stress distribution in the surrounding bone, and in resorption models, von Mises stress was higher than in nonresorption models. Pérez-Pevida et al. (2021) used a 3D model to evaluate the impact of MBL around dental implants and surrounding bone in terms of stress and strain. They concluded that stress distribution of peri-implant bone is higher as the bone loss increases. Yenigun et al. (2021) studied the effect of mono and two-piece abutments on the stress of narrow implants with MBL. Their results report that the marginal bone significantly increased stress values in the implant vicinity and abutment screw. As far as we know, it is still critical to understand the levels of bone loss and their effect on bone tissue mainly with different implant lengths and under different magnitude loading.

Hence, this study aimed to estimate the impact of vertical MBL on stress in the bone around two implants with a difference in length in certain biomechanical conditions: implant A with 12 mm, implant B with 15 mm, and the effect of magnitude loading under axial and buccolingual loading.

2. MATERIALS AND METHODS

2.1 Construction of the 3D Model

Figure 1(a) shows the two scales of bone tissue (micro- and macroscale). Based on scanned mandibular bone surfaces, the macroscale computer-aided design model of the mandible bone was simplified into one section for the computational cost, and it was designed in nonuniform rational basis spline using Rhinoceros 3D v6.0. The cancellous bone

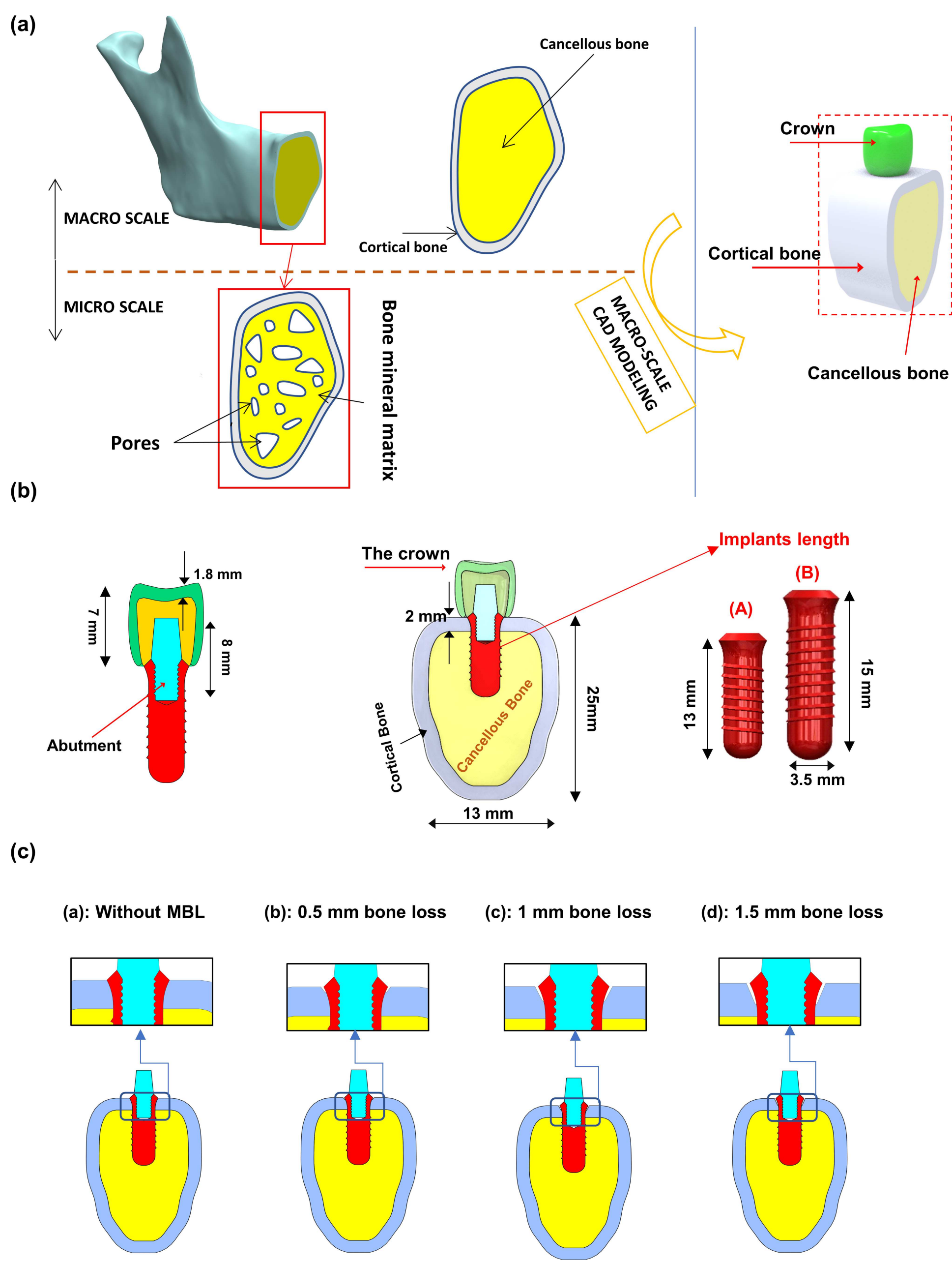

FIG. 1: Construction of 3D models. (a) 3D morphology of selected bone and dental crown; (b) dimensions of different components of the dental system; (c) the studied cases (no MBL, with MBL).

is surrounded by a 2 mm layer of cortical bone (bone type III), and the same steps were done for the dental crown (premolar placement).

Two implants with different lengths and one abutment were constructed in SOLIDWORKS 2020 SP5. Implant A was selected with a length of 12 mm and implant B with 15 mm; both have the same diameter of 3.5 mm as shown in Fig. 1(b). Both implants have the same thread parameters: depth 0.20 mm and pitch 1 mm. The abutment length is 8 mm, the top and the lower diameters are 3 mm and 2.2 mm, respectively. The lower part of the abutment has a thread with a pitch of 0.45 mm and a depth of 0.15 mm.

The purpose of this study was to assess the quantity of MBL around two implants that have a difference in length simulated under axial and buccolingual loading. Four cases were provided as shown in Fig. 1(c): case (a) without MBL, case (b) with 0.5 mm bone loss, case (c) with 1 mm bone loss, and case (d) with 1.5 mm bone loss.

2.2 Mesh and Boundary Settings

All models were imported into the FEA software ABAQUS v6.20, a quadratic tetrahedral element (C3D10) was used for the interested regions between bone and implant interface, and the rest of the components were meshed by linear tetrahedral elements (C3D4) as shown in Fig. 2(a). Mesh sensitivity analysis was performed for more accurate results. The total numbers of elements and nodes of all models are reported in Table 1.

All materials simulated in this study were considered isotropic, homogeneous, and linearly elastic. Table 2 summarizes the properties of the materials used in this study.

The first part was to evaluate the effect of implant length on stress and displacement distribution in the surrounding bone with and without MBL. An axial load of 100 N and a buccolingual load of 50 N were applied separately on

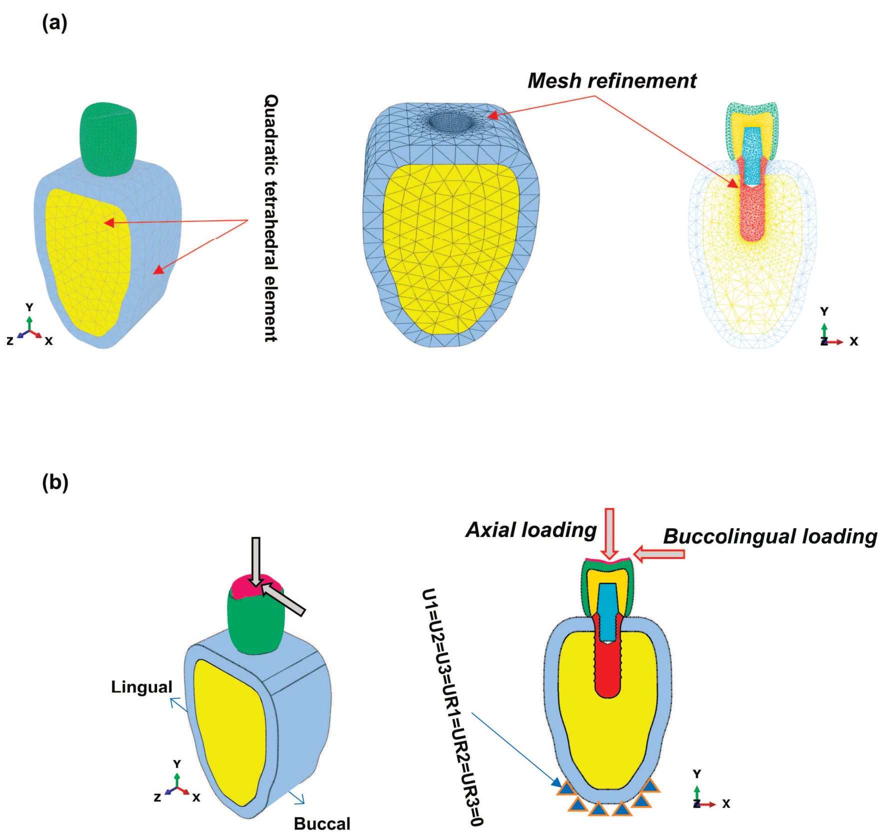

FIG. 2: (a) 3D finite element mesh; (b) loading and boundary conditions

TABLE 1: Total number of nodes and elements used in this study

Implants	Cases	Number of nodes	Number of elements
Implant A	(a) Without bone loss	111,167	230,814
	(b) 0.5 mm bone loss	113,639	232,401
	(c) 1 mm bone loss	111,307	230,949
	(d) 1.5 mm bone loss	113,092	231,984
Implant B	(a) Without bone loss	129,371	247,543
	(b) 0.5 mm bone loss	131,776	249,082
	(c) 1 mm bone loss	130,768	248,438
	(d) 1.5 mm bone loss	130,509	248,245

TABLE 2: Properties of the materials

Components	Materials	Young's modulus (GPa)	Poisson's ratio (ν)	References
Mandibular bone	Cortical bone	13.7	0.3	(Ercal et al., 2021)
	Cancellous bone	1.37		
Abutment-implant	Titanium	100	0.35	(Lemos et al., 2021)
Crown framework	Ni-Cr Alloy	206.0	0.33	
Veneering crown	Feldspar porcelain (ceramic)	82.8	0.35	

the top surface of the veneering crown (all nodes included). In the second part of this study, we examined the influence of load magnitude on stress distribution in the surrounding bone, and different values of loading were applied separately: axial loading (100 N, 150 N, 200 N, 250 N) and buccolingual loading (50 N, 100 N, 150 N, 200 N). The upper surfaces of the bone were fixed in all axes. Figure 2(b) illustrates the boundary conditions. The implant was considered to be fully osseointegrated in this study, and a bonded contact was used for implant–cortical/cancellous bones and bone–bone, based on previous studies (Didier et al., 2020; Shi et al., 2017).

3. RESULTS

3.1 Effect of Implant Length

The influence of two different implant lengths in the surrounding bone was investigated using FEA. Maximum output values are reported in Table 3.

Figure 3 shows the displacement distribution (μm) in the surrounding bone for each implant type. The simulated results show the different displacement of bone tissue (Fig. 3) under axial and buccolingual loading for different implant lengths. The higher displacement was observed in the peri-implant neck area and then gradually decreased at the apical region of the cancellous bone. It could be noticed that in all cases, the higher displacements were with implant A compared to implant B. The maximum displacement was 4.20 μm with implant A and 4.10 μm with implant B, and lowest values were 1.73 μm and 1.59 μm for implants A and B, respectively.

The von Mises stresses distribution (in MPa) of each model in cortical bone and cancellous bone under axial loading are presented in Fig. 4, and under buccolingual loading in Fig. 5. Under axial loading of 100 N, the von Mises stress values are concentrated primarily on the cervical margin of the cortical bone in the region of the implant neck. According to the results obtained in Table 3, the higher stress in cortical bone for implants A and B were 15.6 MPa and 16.1 MPa, respectively. The lowest stress was observed in implant A with a value of 12.9 MPa and for implant B, 13.3 MPa. In cancellous bone, the higher stress for implants A and B were 1.46 MPa and 1.26 MPa, respectively. The minimum stress in cancellous bone with implant B reached a value of 0.95 MPa, and for implant A it was 1.12 MPa. Under buccolingual loading, the maximum stresses in cortical bone for implants A and B were 59.50 MPa and

TABLE 3: Max von Mises stress (MPa) and max displacement (μm) in the cortical bone and the cancellous bone

	Cortical bone				Cancellous bone			
	Axial loading		BL loading		Axial loading		BL loading	
Implant A								
(a) No marginal bone loss	12.9	1.85	43.13	2.83	1.12	1.73	1.28	1.64
(b) 0.5 mm bone loss	14.2	2.10	45.48	3.23	1.24	1.93	1.71	1.85
(c) 1 mm bone loss	14.8	2.34	52.61	3.75	1.38	2.18	2.67	2.52
(d) 1.5 mm bone loss	15.6	2.45	59.50	4.20	1.46	2.34	3.79	3.20
Implant B								
(a) No marginal bone loss	13.3	1.70	45.02	2.80	0.95	1.59	1.27	1.61
(b) 0.5 mm bone loss	14.9	1.94	48.54	3.21	1.05	1.77	1.72	1.80
(c) 1 mm bone loss	15.2	2.12	55.56	3.68	1.17	1.97	2.56	2.47
(d) 1.5 mm bone loss	16.1	2.25	62.57	4.10	1.26	2.10	3.73	3.19

62.57 MPa, respectively. In cancellous bone, the peak stress for implant A was 3.79, and 3.73 MPa for implant B, and the minimum stresses for implants A and B were 1.28 MPa and 1.23 MPa, respectively. The results indicate that the stress values were much higher in cortical bone compared to the cancellous bone and that buccolingual loading generates more stress than axial loading. It could be also noticed that the stress between cancellous bone and implant interface under axial loading tends to decrease with the increasing length of the implant.

3.2 Effect of Bone Loss Levels

From the outputs results, for implant A, the maximum displacement was 4.20 μm in case (d) with 1.5 mm bone loss, and the lowest value was 1.64 μm in the case of no MBL. For implant B, the maximum displacement was in the case of 1.5 mm bone loss (4.10 μm) and the minimum value in case (a) without MBL (1.61 μm). It could be observed that the maximum displacements were higher with increasing amounts of MBL. Stress analysis showed that the amount of bone loss increased the equivalent stress in cortical and cancellous bone. In models of no MBL, the stress was less. Conversely, in the case of MBL, the stresses were higher. Maximum stress was obtained with case (d): 62.57 MPa in cortical bone and 3.73 MPa in cancellous bone. Lower stress was observed in case (a) without MBL, 13.3 MPa in cortical bone, 0.95 MPa in cancellous bone. Stress analysis in the bone tissue under different loading showed that increasing the bone loss levels increases the stress and that buccolingual loading produces more stress than axial loading. The maximum stresses of cortical bone were less than the yield strength, around 113 MPa (Reed and Brown, 2001). For the cancellous bone, the peak stress values under axial loading in all cases were lower than the yield strength (around 3.65 MPa) (Zhang et al., 2013; Nazarian et al., 2009), but in buccolingual loading for both implants, the maximum stress in case (d) with 1.5 bone loss was higher compared to the yield strength.

3.3 Effect of Loading

Overload in a biomechanical system is characterized as a situation in which excessive mastication forces cause the implant or mechanical components to bend repeatedly, resulting in MBL or implant failure. To study the influence of the excessive loads and the MBL, four loads were applied separately with implant A in different directions: axial loading of 100 N, 150 N, 200 N, and 250 N and buccolingual loading of 50 N, 100 N, 150 N, and 200 N. Figures 6 and 7 show the stress change in terms of different loading and MBL levels. Results indicate that progressive bone loss with excessive loading increase the stress intensity in cortical and cancellous bone and may lead to catastrophic

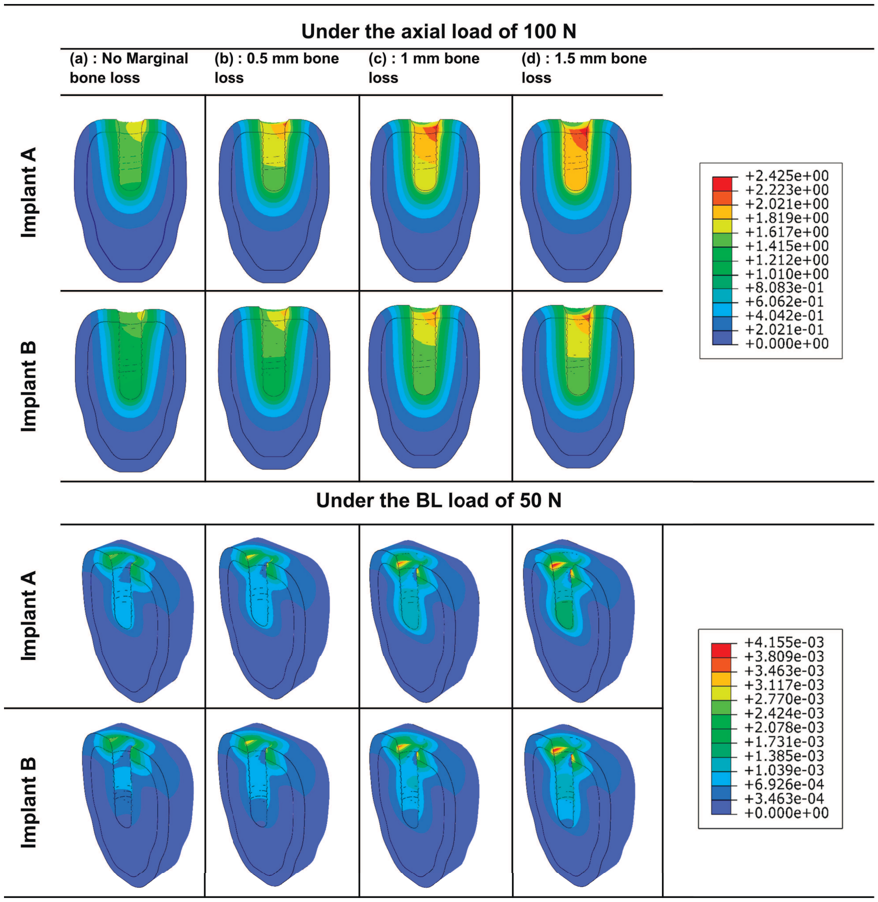

FIG. 3: Displacement distribution (μm) under axial load in cortical and cancellous bone. Case (a) without marginal bone loss; cases (b)–(d) with marginal bone loss.

fracture of the mandible bone. Excessive chewing forces are a very influential factor in disrupting the osseointegration process.

4. DISCUSSION

One of the main criteria for determining implant success has always been marginal bone stability around implants, and many causes have been suggested to contribute to MBL around the dental implant, including bacterial infiltration, implant neck design, and undesirable stress distribution surrounding the bone (Paracchini et al., 2020). Moreover, several studies have been introduced to improve implant stability and reduce MBL (Díaz-Sánchez et al., 2019; Lombardi et al., 2019).

This study with each simulated model was carried out to study the effect of the amount of bone loss, including the implant length and magnitude loading on the stress distribution in the surrounding bone using FEA. Von Mises stress (equivalent stress) is often used as a technique for the evaluation of stress in FEA of 3D bodies with complex shapes such as teeth or mandible (Shinya et al., 2021). Results showed that the difference between the length of the implants does not affect significantly the peak stress value in the bones, but rather on its distribution. Longer implants may contribute to decreasing stress in the cancellous bone compared to short implants, as achieved in the previous study (Raaj et al., 2019). Longer implants contribute to more stress inside the bone. Von Mises stresses were higher in cortical bone compared to cancellous bone due to the variation between stiffness; cortical bone is stiffer and able

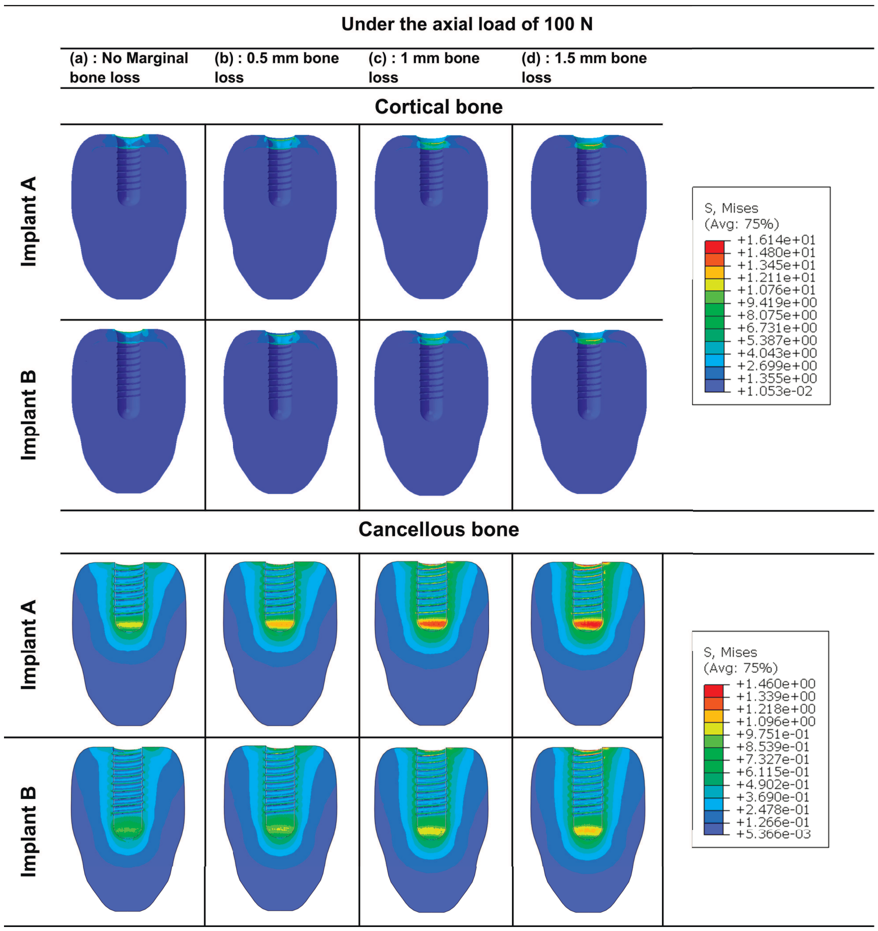

FIG. 4: Stress distribution in MPa under axial load in cortical and cancellous bone. Case (a) without marginal bone loss; cases (b)–(d) with marginal bone loss.

to resist more compression than cancellous bone (Morgan et al., 2018). The current study's findings showed that the maximum amount of stress in cortical and cancellous bone is concentrated around the neck at the bone–implant interface, and the stresses under buccolingual loading were higher than axial loading. This is because of the shear forces created under buccolingual loading, which acts parallel to the surface, and that axial loading acts uniformly along with the implant. The results of this study coincide with other studies showing that progressive bone loss contributed to an increase of stress in the bone (Yoon et al., 2011). The bone loss amounts are usually at the first year after implantation because of mechanical damage during drilling procedure surgery (Pérez-Pevida et al., 2020). The drilling forces created are highly subjective, and they vary depending on the clinician (Lughmani et al., 2015). The pocket formed in the bone by the MBL may allow bacterial colonization, which may affect the remodeling process of the cancellous bone in the long term (Pokrowiecki et al., 2017).

One of the main factors for bone loss is occlusal overload; to understand the impact of bite forces an increase of load magnitude was applied in this study. Results showed excessive loading and progressive bone loss increase the stress in cortical and cancellous bone. The greater masticatory load with a greater duration of contact can cause deformation and pathological mandibular fracture (Sohn et al., 2011), bone damage, or implant failure due to excessive force around the implant (Marcián et al., 2018).

Higher stress generated in the bone tissue may lead to an increase in stress and strain intensity. Frost's (2001) study proved that the bones can be remodeled according to the amount of internal stress. If the threshold is exceeded,

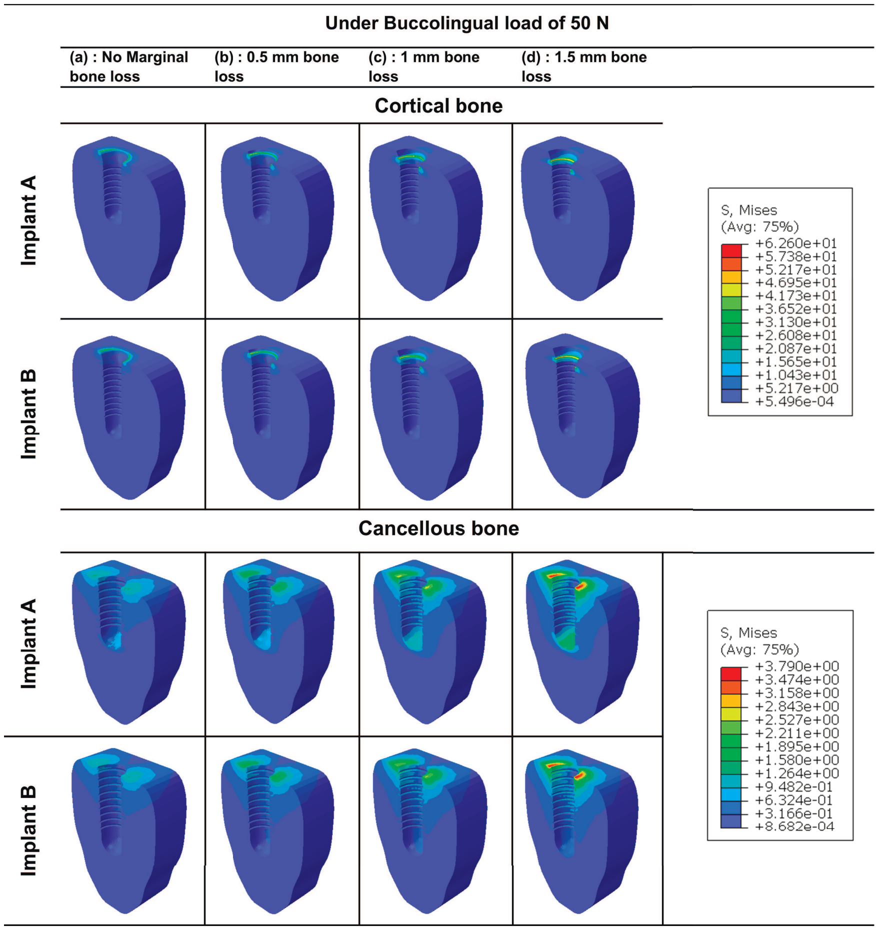

FIG. 5: Stress distribution in MPa under buccolingual load in cortical and cancellous bone. Case (a) without marginal bone loss; cases (b)–(d) with marginal bone loss.

the result will be bone loss or pathological overload, which cause bone damage or mini fractures. This is what was updated in mechanostat hypothesis (Frost, 2004), which describes the state of bone behavior depending on the stress and strain severity.

Studies have proven the necessity to look at the patient's bone condition as an important factor for implantation (Chakraborty et al., 2020). In addition, measurements of primary implant stability provide important predictive information that may aid treatment planning (de Souza et al., 2013). To our knowledge, no FEA data are reported in the literature on how overload and MBL with different implant lengths can contribute to increasing stresses in the bone tissue. Therefore, we couldn't compare the output data of the current study with other FEA studies. However, we could demonstrate the effect of MBL with different loading and different implant length on stress distribution in the bone. The study will be extended in the future to include an algorithm of the healing process of the surrounding bone after excessive bone loss.

Establishing bone geometry and then adopting FEA is one approach to solving problems in biomechanics (Fish and Hu, 2016). On the other hand, multiscale analysis has gradually gained enormous potential for combined macro- and microanalysis in the field of bioengineering tissues (Sanz-Herrera et al., 2019). In this study, we were able to numerically determine how much stress was distributed using FEA, but we are unable to perform a clinical experiment for this study, which has some limitations. FEA tool cannot account for the effects of forces applied by oral cavity muscles. Bone properties are overly complex, and their behavior cannot act as isotropic and homogenous. As well as

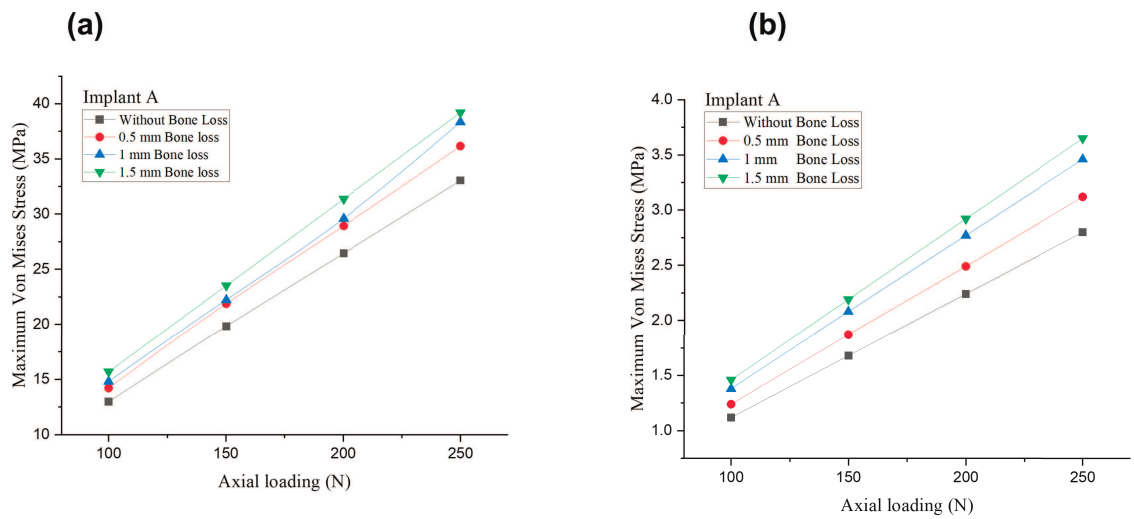

FIG. 6: Variation of von Mises stress with axial loading with different bone loss levels: (a) cortical bone; (b) cancellous bone

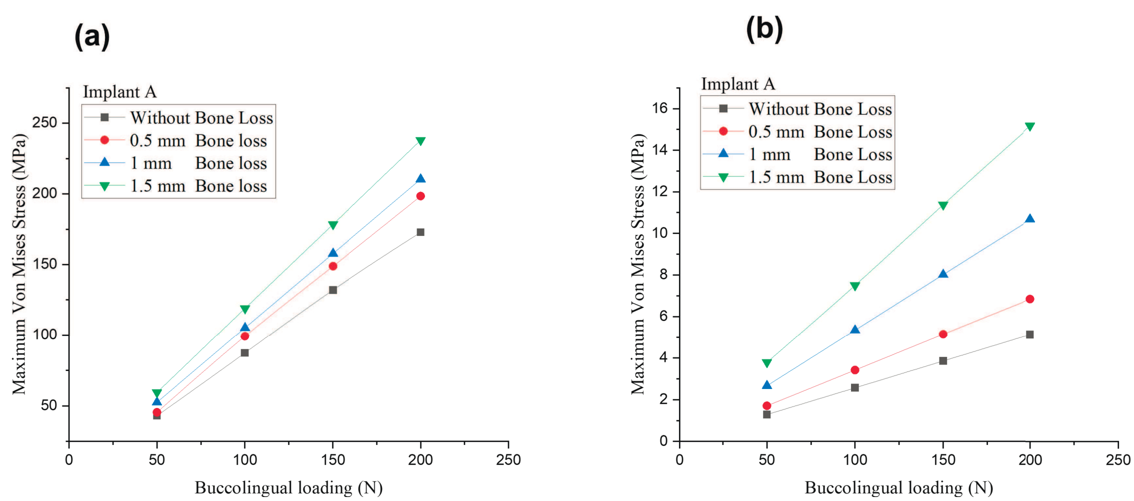

FIG. 7: Variation of von Mises stress with buccolingual loading with different bone loss levels: (a) cortical bone; (b) cancellous bone

in the case that was studied, the role of the gums was not considered. However, it is necessary to compare the presented results with those obtained by *in vivo* studies. Despite this, the study will be extended in the future to predict the field variable distribution (stresses, strains) at both scales (macro and micro) using the powerful tool, FEA.

5. CONCLUSION

MBL is still a serious problem. In this study, the stress between the bone–implant interface has been studied using FEA, and with the limitation of this study, it was concluded that:

1. The stresses between cancellous bone and implant interface under axial loading tend to decrease with the increase of implant length.
2. Regardless of the implant length, progressive MBL and excessive loading produce higher stresses in the bone tissue.

3. A nonaxial loading generates more stresses in the bone tissue than the axial loading.

These factors may affect the bone remodeling process and can lead to implant failure.

REFERENCES

Al-Thobity, A.M., Kutkut, A., and Almas, K., Microthreaded Implants and Crestal Bone Loss: A Systematic Review, *J. Oral Implantol.*, vol. **43**, no. 2, pp. 157–166, 2017. DOI: 10.1563/aaid-joi-D-16-00170

Albrektsson, T., Becker, W., Coli, P., Jemt, T., Mölne, J., and Sennerby, L., Bone Loss around Oral and Orthopedic Implants: An Immunologically Based Condition, *Clin. Implant Dentistry and Related Res.*, vol. **21**, no. 4, pp. 786–795, 2019. DOI: 10.1111/cid.12793

Albrektsson, T., Jemt, T., Mölne, J., Tengvall, P., and Wennerberg, A., On Inflammation-Immunological Balance Theory—A Critical Apprehension of Disease Concepts around Implants: Mucositis and Marginal Bone Loss May Represent Normal Conditions and Not Necessarily a State of Disease, *Clin. Implant Dentistry Related Res.*, vol. **21**, no. 1, pp. 183–189, 2019. DOI: 10.1111/cid.12711

Alemayehu, D.B. and Jeng, Y.R., Three-Dimensional Finite Element Investigation into Effects of Implant Thread Design and Loading Rate on Stress Distribution in Dental Implants and Anisotropic Bone, *Materials*, vol. **14**, no. 22, pp. 6974–6997, 2021. DOI: 10.3390/ma14226974

Ali, B., Meddah, H.M., and Merdji, A., Effects of Overloading in Mastication on the Mechanical Behaviour of Dental Implants, *Mater. Design*, vol. **47**, pp. 210–217, 2013. DOI: 10.1016/j.matdes.2012.12.019

Anitua, E., Larrazabal Saez de Ibarra, N., Morales Martín, I., and Saracho Rotaeche, L., Influence of Dental Implant Diameter and Bone Quality on the Biomechanics of Single-Crown Restoration. A Finite Element Analysis, *Dentistry J.*, vol. **9**, no. 9, pp. 103–114, 2021. DOI: 10.3390/dj9090103

Ausiello, P., Tribst, J.P.M., Ventre, M., Salvati, E., Di Lauro, A.E., Martorelli, M., and Watts, D.C., The Role of Cortical Zone Level and Prosthetic Platform Angle in Dental Implant Mechanical Response: A 3D Finite Element Analysis, *Dental Mater.*, vol. **37**, no. 11, pp. 1688–1697, 2021. DOI: 10.1016/j.dental.2021.08.022

Ayranci, F., Sivrikaya, E.C., and Omezli, M.M., Is Bone Density or Implant Design More Important in Implant Stress Formation in Patients with Bruxism?, *Biotechnol. Equip.*, vol. **31**, no. 6, pp. 1221–1225, 2017. DOI: 10.1080/13102818.2017.1376597

Bing, L., Mito, T., Yoda, N., Sato, E., Shigemitsu, R., Han, J.M., and Sasaki, K., Effect of Peri-Implant Bone Resorption on Mechanical Stress in the Implant Body: In Vivo Measured Load-Based Finite Element Analysis, *J. Oral Rehabil.*, vol. **47**, no. 12, pp. 1566–1573, 2020. DOI: 10.1111/joor.13097

Boukhlif, A., Merdji, A., Sandipan, R., Hashem, A., Ibrahim, A., Nourddine, D., Corina, M., and Rajshree, H., Effect of Supporting Implants Inclination on Stability of Fixed Partial Denture: A Finite Element Study, *Proc. Inst. Mechan. Eng., Part H: J. Eng. Med.*, vol. **234**, no. 10, pp. 1162–1171. DOI: 10.1177/0954411920944109

Chakraborty, A., Datta, P., Majumder, S., Mondal, S.C., and Roychowdhury, A., Finite Element and Experimental Analysis to Select Patient's Bone Condition Specific Porous Dental Implant, Fabricated Using Additive Manufacturing, *Comput. Bio. Med.*, vol. **124**, pp. 103839–103849, 2020. DOI: 10.1016/j.compbiomed.2020.103839

Chrcanovic, B.R., Albrektsson, T., and Wennerberg, A., Smoking and Dental Implants: A Systematic Review and Meta-Analysis, *J. Dentistry*, vol. **43**, no. 5, pp. 487–498, 2015. DOI: 10.1016/j.jdent.2015.03.003

Chrcanovic, B.R., Kisch, J., Albrektsson, T., and Wennerberg, A., A Retrospective Study on Clinical and Radiological Outcomes of Oral Implants in Patients Followed up for a Minimum of 20 Years, *Clin. Implant Dentistry Related Res.*, vol. **20**, no. 2, pp. 199–207, 2018. DOI: 10.1111/cid.12571

Clementini, M., Rossetti, P.H.O., Penarrocha, D., Micarelli, C., Bonachela, W.C., and Canullo, L., Systemic Risk Factors for Peri-Implant Bone Loss: A Systematic Review and Meta-Analysis, *Int. J. Oral Maxillofac. Surg.*, vol. **43**, no. 3, pp. 323–334, 2014. DOI: 10.1016/j.ijom.2013.11.012

Díaz-Sánchez, R.M., Delgado-Muñoz, J.M., Serrera-Figallo, M.Á., González-Martín, M.I., Torres-Lagares, D., and Gutiérrez-Pérez, J.L., Analysis of Marginal Bone Loss and Implant Stability Quotient by Resonance Frequency Analysis in Different Osteointegrated Implant Systems, *Randomized Prospective Clinical Trial, Medicina Oral, Patologia Oral y Cirugia Buccal.*, vol. **24**, no. 2, pp. e260–e264, 2019. DOI: 10.4317/medoral.22742

Didier, P., Piotrowski, B., Le Coz, G., Joseph, D., Bravetti, P., and Laheurte, P., Finite Element Analysis of the Stress Field in

Peri-Implant Bone: A Parametric Study of Influencing Parameters and Their Interactions for Multi-Objective Optimization, *Appl. Sci.*, vol. **10**, no. 17, pp. 5973–5988, 2020. DOI: 10.3390/app10175973

Drai, A., Merdji, A., Albedah, A., Bouiadjra, B.A.B., Benyahia, F., and Mohammed, S.M., Effect of Dental Implantology on the Biomechanical Behavior of Alveolar Bone, *Int. J. Multiscale Comput. Eng.*, vol. **16**, no. 6, pp. 579–593, 2018. DOI: 10.1615/IntJMultCompEng.2018028717

Duan, X.B., Wu, T.X., Guo, Y.C., Zhou, X.D., Lei, Y.L., Xu, X., and Yuan, Q., Marginal Bone Loss around Non-Submerged Implants Is Associated with Salivary Microbiome during Bone Healing, *Int. J. Oral Sci.*, vol. **9**, no. 2, pp. 95–103, 2017. DOI: 10.1038/ijos.2017.18

Ercal, P., Taysi, A.E., Ayvalioglu, D.C., Eren, M.M., and Sismanoglu, S., Impact of Peri-Implant Bone Resorption, Prosthetic Materials, and Crown to Implant Ratio on the Stress Distribution of Short Implants: A Finite Element Analysis, *Med. Bio. Eng. Comput.*, vol. **59**, no. 4, pp. 813–824, 2021. DOI: 10.1007/s11517-021-02342-w

Fish, J. and Hu, N., Multiscale Modeling of Femur Fracture, *Int. J. Numer. Methods Eng.*, vol. **111**, no. 1, pp. 3–25, 2017. DOI: 10.1002/nme.5450

Frost, H.M., From Wolff's Law to the Utah Paradigm: Insights about Bone Physiology and Its Clinical Applications, *Anatomical Record: An Official Publ. Am. Assoc. Anatomists*, vol. **262**, no. 4, pp. 398–419, 2001. DOI: 10.1002/ar.1049

Frost, H.M., A 2003 Update of Bone Physiology and Wolff's Law for Clinicians, *Angle Orthodont.*, vol. **74**, no. 1, pp. 3–15, 2004. DOI: 10.1043/0003-3219(2004)074%3C0003:auobpa%3E2.0.co;2

González-Serrano, J., Vallina, C., González-Serrano, C., Sánchez-Monescillo, A., Torres, J., Hernández, G., and López-Pintor, R.M., Effect of Platelet Concentrates on Marginal Bone Loss of Immediate Implant Procedures: A Systematic Review and Meta-Analysis, *Materials*, vol. **14**, no. 16, pp. 4582–4604, 2021. DOI: 10.3390/ma14164582

Gupta, S., Chopra, P., Goyal, P., and Jain, A., Effect of Vertical Bone Loss on Stress Distribution at the Bone-Implant Interface around Implants of Varying Diameters—An in Silico 3D Finite Element Analysis, *Mater. Today: Proc.*, vol. **45**, pp. 4581–4586, 2021. DOI: 10.1016/j.matpr.2021.01.008

Kasani, R., Attili, B.K.R.S., Dommeti, V.K., Merdji, A., Biswas, J.K., and Roy, S., Stress Distribution of Overdenture Using Odd Number Implants—A Finite Element Study, *J. Mechan. Behavior Biomed. Mater.*, vol. **98**, pp. 369–382, 2019. DOI: 10.1016/j.jmbbm.2019.06.030

Kim, Y.T., Lim, G.H., Lee, J.H., and Jeong, S.N., Marginal Bone Level Changes in Association with Different Vertical Implant Positions: A 3-Year Retrospective Study, *J. Periodont. Implant Sci.*, vol. **47**, no. 4, pp. 231–239, 2017. DOI: 10.5051/jpis.2017.47.4.231

Korkmaz, I.H. and Kul, E., Investigation of the Type of Angled Abutment for Anterior Maxillary Implants: A Finite Element Analysis, *J. Prosthodont.*, 2021. DOI: 10.1111/jopr.13462

Kowalski, J., Lapinska, B., Nissan, J., and Lukomska-Szymanska, M., Factors Influencing Marginal Bone Loss around Dental Implants: A Narrative Review, *Coatings*, vol. **11**, no. 7, p. 865, 2021. DOI: 10.3390/coatings11070865

Lemos, C.A.A., Verri, F.R., Noritomi, P.Y., Kemmoku, D.T., de Souza Batista, V.E., Cruz, R.S., de Luna Gomes, J.M., and Pellizzer, E.P., Effect of Bone Quality and Bone Loss Level around Internal and External Connection Implants: A Finite Element Analysis Study, *J. Prosthetic Dentistry*, vol. **125**, no. 1, pp. 137–147, 2021. DOI: 10.1016/j.prosdent.2020.06.029

Linetskiy, I., Demenko, V., Linetska, L., and Yefremov, O., Impact of Annual Bone Loss and Different Bone Quality on Dental Implant Success—A Finite Element Study, *Comput. Bio. Med.*, vol. **91**, pp. 318–325, 2017. DOI: 10.1016/j.compbiomed.2017.09.016

Lombardi, T., Berton, F., Salgarello, S., Barbalonga, E., Rapani, A., Piovesana, F., and Stacchi, C., Factors Influencing Early Marginal Bone Loss around Dental Implants Positioned Subcrestally: A Multicenter Prospective Clinical Study, *J. Clin. Med.*, vol. **8**, no. 8, pp. 1168–1181, 2019. DOI: 10.3390/jcm8081168

Lughmani, W.A., Bouazza-Marouf, K., and Ashcroft, I., Drilling in Cortical Bone: A Finite Element Model and Experimental Investigations, *J. Mechan. Behavior Biomed. Mater.*, vol. **42**, pp. 32–42, 2015. DOI: 10.1016/j.jmbbm.2014.10.017

Mailoa, J., Fu, J.H., Chan, H.L., Khoshkam, V., Wang, H.L., and Li, J., The Effect of Vertical Implant Position in Relation to Adjacent Teeth on Marginal Bone Loss in Posterior Arches: A Retrospective Study, *Int. J. Oral Maxillofac. Implants*, vol. **30**, no. 4, pp. 931–936, 2015. DOI: 10.11607/jomi.4067

Marcián, P., Wolff, J., Horáčková, L., Kaiser, J., Zikmund, T., and Borák, L., Micro Finite Element Analysis of Dental Implants under Different Loading Conditions, *Comput. Bio. Med.*, vol. **96**, pp. 157–165, 2018. DOI: 10.1016/j.compbiomed.2018.03.012

Mehboob, H., Mehboob, A., Abbassi, F., Ahmad, F., Khan, A.S., and Miran, S., Bioinspired Porous Dental Implants Using the Concept of 3D Printing to Investigate the Effect of Implant Type and Porosity on Patient's Bone Condition, *Mechan. Adv. Mater. Struct.*, pp. 1–15, 2021. DOI: 10.1080/15376494.2021.1971347

Merdji, A., Bouiadjra, B.B., Chikh, B.O., Mootanah, R., Aminallah, L., Serier, B., and Muslih, I.M., Stress Distribution in Dental Prosthesis under an Occlusal Combined Dynamic Loading, *Mater. Design (1980–2015)*, vol. **36**, pp. 705–713, 2012. DOI: 10.1016/j.matdes.2011.12.006

Morgan, E.F., Unnikrisnan, G.U., and Hussein, A.I., Bone Mechanical Properties in Healthy and Diseased States, *Annual Rev. Biomed. Eng.*, vol. **20**, pp. 119–143, 2018. DOI: 10.1146/annurev-bioeng-062117-121139

Nandal, S., Ghalaut, P., and Shekhawat, H., A Radiological Evaluation of Marginal Bone around Dental Implants: An in-Vivo Study, *Natl. J. Maxillofac. Surg.*, vol. **5**, no. 2, pp. 126–137, 2014. DOI: 10.4103/0975-5950.154813

Naveau, A., Shinmyouzu, K., Moore, C., Avivi-Arber, L., Jokerst, J., and Koka, S., Etiology and Measurement of Peri-Implant Crestal Bone Loss (CBL), *J. Clin. Med.*, vol. **8**, no. 2, pp. 166–186, 2019. DOI: 10.3390/jcm8020166

Nazarian, A., Meier, D., Müller, R., and Snyder, B.D., Functional Dependence of Cancellous Bone Shear Properties on Trabecular Microstructure Evaluated Using Time-Lapsed Micro-Computed Tomographic Imaging and Torsion Testing, *J. Ortho. Res.*, vol. **27**, no. 12, pp. 1667–1674, 2009. DOI: 10.1002/jor.20931

Nimbalkar, S., Dhatrak, P., Gherde, C., and Joshi, S., A Review Article on Factors Affecting Bone Loss in Dental Implants, *Mater. Today: Proc.*, vol. **43**, pp. 970–976, 2021. DOI: 10.1016/j.matpr.2020.07.428

Ormianer, Z., Matalon, S., Block, J., and Kohen, J., Dental Implant Thread Design and the Consequences on Long-Term Marginal Bone Loss, *Implant Dentistry*, vol. **25**, no. 4, pp. 471–477, 2016. DOI: 10.1097/ID.0000000000000441

Ouldyerou, A., Aminallah, L., Merdji, A., Mehboob, A., and Mehboob, H., Finite Element Analyses of Porous Dental Implant Designs Based on 3D Printing Concept to Evaluate Biomechanical Behaviors of Healthy and Osteoporotic Bones, *Mechan. Adv. Mater. Struct.*, pp. 1–13, 2022. DOI: 10.1080/15376494.2022.2053908

Oliveira de Souza, J.G., Lopes Pereira Neto, A.R., Schuldt Filho, G., Renata Dalago, H., Moisés de Souza Júnior, J., and Aurélio Bianchini, M., Impact of Local and Systemic Factors on Additional Peri-Implant Bone Loss, *Quint. Int.*, vol. **44**, no. 5, pp. 415–424, 2013. DOI: 10.3290/j.qi.a29152

Paracchini, L., Barbieri, C., Redaelli, M., Di Croce, D., Vincenzi, C., and Guarnieri, R., Finite Element Analysis of a New Dental Implant Design Optimized for the Desirable Stress Distribution in the Surrounding Bone Region, *Prosthesis*, vol. **2**, no. 3, pp. 225–236, 2020. DOI: 10.3390/prosthesis2030019

Pérez-Pevida, E., Chávarri-Prado, D., Diéguez-Pereira, M., Estrada-Martínez, A., Montalbán-Vadillo, O., and Jiménez-Garrudo, A., Consequences of Peri-Implant Bone Loss in the Occlusal Load Transfer to the Supporting Bone in Terms of Magnitude of Stress, Strain, and Stress Distribution: A Finite Element Analysis, *BioMed Res. Int.*, vol. **2021**, pp. 1–10, 2021. DOI: 10.1155/2021/3087071

Pérez-Pevida, E., Cherro, R., Camps, O., and Piqué, N., Effects of Drilling Protocol and Bone Density on the Stability of Implants According to Different Macrogeometries of the Implant Used: Results of an in Vitro Study, *Int. J. Oral Maxillofac. Implants*, vol. **35**, no. 5, pp. 955–964, 2020. DOI: 10.11607/jomi.8176

Pokrowiecki, R., Mielczarek, A., Zareba, T., and Tyski, S., Oral Microbiome and Peri-Implant Diseases: Where Are We Now, *Therap. Clin. Risk Manage.*, vol. **13**, pp. 1529–1542, 2017. DOI: 10.2147/TCRM.S139795

Qu, C., Luo, F., Hong, G., and Wan, Q., Effects of Platelet Concentrates on Implant Stability and Marginal Bone Loss: A Systematic Review and Meta-Analysis, *BMC Oral Health*, vol. **21**, no. 1, pp. 1–16, 2021. DOI: 10.1186/s12903-021-01929-x

Raaj, G., Manimaran, P., Kumar, C.D., Sadan, D.S., and Abirami, M., Comparative Evaluation of Implant Designs: Influence of Diameter, Length, and Taper on Stress and Strain in the Mandibular Segment—A Three-Dimensional Finite Element Analysis, *J. Pharm. Bioallied Sci.*, vol. **11**, no. 2, pp. S347–S354, 2019. DOI: 10.4103/JPBS.JPBS_29_19

Ramanauskaite, A., Roccuzzo, A., and Schwarz, F., A Systematic Review on the Influence of the Horizontal Distance between Two Adjacent Implants Inserted in the Anterior Maxilla on the Inter-Implant Mucosa Fill, *Clin. Oral Implants Res.*, vol. **29**, pp. 62–70, 2018. DOI: 10.1111/clr.13103

Ramos, A. and Mesnard, M., Finite Element Model to Predict Bone Loss around Dental Implant, *Comp. Methods Biomechan. Biomed. Eng.*, vol. **22**, no. 1, pp. S48–S50, 2019. DOI: 10.1080/10255842.2020.1713474

Reddy, M.S., Sundram, R., and Abdemagyd, H.A.E., Application of Finite Element Model in Implant Dentistry: A Systematic Review, *J. Pharm. Bioallied Sci.*, vol. **11**, no. 2, pp. S85–S91, 2019. DOI: 10.4103/JPBS.JPBS_296_18

Reed, K.L. and Brown, T.D., Elastic Modulus and Strength of Emu Cortical Bone, *Iowa Ortho. J.*, vol. **21**, pp. 53–57, 2001.

Revilla-León, M., Sadeghpour, M., and Özcan, M., A Review of the Applications of Additive Manufacturing Technologies Used to Fabricate Metals in Implant Dentistry, *J. Prosthodont.*, vol. **29**, no. 7, pp. 579–593, 2020. DOI: 10.1111/jopr.13212

Sadowsky, S.J., Occlusal Overload with Dental Implants: A Review, *Int. J. Implant Dentistry*, vol. **5**, no. 1, pp. 1–5, 2019. DOI: 10.1186/s40729-019-0180-8

Sanz-Herrera, J.A., Mora-Macías, J., Reina-Romo, E., Domínguez, J., and Doblaré, M., Multiscale Characterisation of Cortical Bone Tissue, *Appl. Sci.*, vol. **9**, no. 23, pp. 5228–5245, 2019.

Saravi, B.E., Putz, M., Patzelt, S., Alkalak, A., Uelkuemen, S., and Boeker, M., Marginal Bone Loss around Oral Implants Supporting Fixed versus Removable Prostheses: A Systematic Review, *Int. J. Implant Dentistry*, vol. **6**, no. 1, pp. 1–9, 2020. DOI: 10.1186/s40729-020-00217-7

Shi, M., Li, H., and Liu, X., Multidisciplinary Design Optimization of Dental Implant Based on Finite Element Method and Surrogate Models, *J. Mechan. Sci. Technol.*, vol. **31**, no. 10, pp. 5067–5073, 2017. DOI: 10.1007/s12206-017-0955-x

Shinya, A., Ishida, Y., Miura, D., and Shinya, A., The Effect of Implant Length and Diameter on Stress Distribution around Single Implant Placement in 3D Posterior Mandibular FE Model Directly Constructed Form in Vivo CT, *Materials*, vol. **14**, no. 23, p. 7344, 2021. DOI: 10.3390/ma14237344

Sohn, B.S., Heo, S.J., Koak, J.Y., Kim, S.K., and Lee, S.Y., Strain of Implants Depending on Occlusion Types in Mandibular Implant-Supported Fixed Prostheses, *J. Adv. Prosthodont.*, vol. **3**, no. 1, pp. 1–9, 2011. DOI: 10.4047/jap.2011.3.1.1

Srinivasan, M., Meyer, S., Mombelli, A., and Müller, F., Dental Implants in the Elderly Population: A Systematic Review and Meta-Analysis, *Clin. Oral Implants Res.*, vol. **28**, no. 8, pp. 920–930, 2017. DOI: 10.1111/clr.12898

Taharou, B., Merdji, A., Hillstrom, R., Benaissa, A., Roy, S., Della, N., Aid, A., and Mukdadi, O., Biomechanical Evaluation of Bone Quality Effect on Stresses at Bone-Implant Interface: A Finite Element Study, *J. Appl. Comput. Mechan.*, vol. **7**, no. 3, pp. 1266–1275, 2020. DOI: 10.22055/JACM.2020.32323.2005

Wolff, J., Narra, N., Antalainen, A.K., Valáček, J., Kaiser, J., Sándor, G.K., and Marcián, P., Finite Element Analysis of Bone Loss around Failing Implants, *Mater. Design*, vol. **61**, pp. 177–184, 2014. DOI: 10.1016/j.matdes.2014.04.080

Yenigun, S., Ercal, P., Ozden-Yenigun, E., and Katiboglu, A.B., Influence of Abutment Design on Stress Distribution in Narrow Implants with Marginal Bone Loss: A Finite Element Analysis, *Int. J. Oral Maxillofac. Implants*, vol. **36**, no. 4, pp. 640–649, 2021. DOI: 10.11607/jomi.8554

Yoon, K.H., Kim, S.G., Lee, J.H., and Suh, S.W., 3D Finite Element Analysis of Changes in Stress Levels and Distributions for an Osseointegrated Implant after Vertical Bone Loss, *Implant Dentistry*, vol. **20**, no. 5, pp. 354–359, 2011. DOI: 10.1097/ID.0b013e318226294b

Zhang, N., Magland, J.F., Rajapakse, C.S., Lam, S.B., and Wehrli, F.W., Assessment of Trabecular Bone Yield and Post-Yield Behavior from High-Resolution MRI-Based Nonlinear Finite Element Analysis at the Distal Radius of Premenopausal and Postmenopausal Women Susceptible to Osteoporosis, *Acad. Radiol.*, vol. **20**, no. 12, pp. 1584–1591, 2013. DOI: 10.1016/j.acra.2013.09.005

Zhang, Q. and Yue, X., Marginal Bone Loss around Machined Smooth Neck Implants Compared to Rough Threaded Neck Implants: A Systematic Review and Meta-Analysis, *J. Prosthodont.*, vol. **30**, no. 5, pp. 401–411, 2021. DOI: 10.1111/jopr.13333