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Finite element analysis on influence of implant surface treatments, connection and bone types☆

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ABSTRACT

The aim of this study is to assess the effect of different dental implant designs, bone type, loading, and surface treatment on the stress distribution around the implant by using the 3D finite-element method. Twelve 3D models were developed with Invesalius 3.0, Rhinoceros 4.0, and Solidworks 2010 software. The analysis was processed using the FEMAP 10.2 and NeiNastran 10.0 software. The applied oblique forces were 200 N and 100 N. The results were analyzed using maps of maximum principal stress and bone microstrain. Statistical analysis was performed using ANOVA and Tukey's test. The results showed that the Morse taper design was most efficient in terms of its distribution of stresses ($p < 0.05$); the external hexagon with platform switching did not show a significant difference from an external hexagon with a standard platform ($p > 0.05$). The different bone types did not show a significant difference in the stress/strain distribution ($p > 0.05$). The surface treatment increased areas of stress concentration under axial loading ($p < 0.05$) and increased areas of microstrain under axial and oblique loading ($p < 0.05$) on the cortical bone. The Morse taper design behaved better biomechanically in relation to the bone tissue. The treated surface increased areas of stress and strain on the cortical bone tissue.

1. Introduction

Dental implants have improved the quality of life for millions of patients in recent decades; further, they have shown high successful predictability [1]. However, one of the main challenges has been to indicate which dental implant design shows the best biomechanical behavior for each existing clinical situation [2,3].

The literature indicates that different biomechanical factors can influence the stress distribution around an implant [2,4,5]. Biomechanically, the effectiveness of a dental implant design is dependent on the way that the stresses are transmitted to the bone tissue [6].

In this context, there is no consensus about the best option for dental implant design, since external hexagon implants show reversibility that is suitable for implant-supported prostheses [3]. Furthermore, longitudinal studies over the course of several years have indicated high survival rates of dental implants [1,7]; however, the external hexagon implants have been associated with rates of bone loss that exceeds 1.5 mm over the years [8], compared to Morse taper and platform-switching implants [7,9,10].

In this respect, the dental implant platform-switching concept (PSW), in which a narrow diameter abutment is placed on an external hexagon implant of a wider diameter, has been associated with lower marginal bone loss [9,11]. Nevertheless, more biomechanical studies are necessary in order to assess this concept in the clinical situation of low-density bone.

Another relevant biomechanical factor is related to the quality of bone type that is available for rehabilitation with dental implants [1,12–14]. Some studies have indicated that type IV bone is more susceptible to biomechanical damage than other bone types (I–III) [5,12,14–16]. Clinically, some studies have reported a higher rate of failure of implants placed in low-density bone [1,17]. However, no study has evaluated the best biomechanical profile of each dental implant design for low-density bone.

Finally, the surface treatments of implants have been indicated as a pertinent factor for the longevity of this modality of treatment [1]. Moreover, the surface treatment in implants placed in low-density bone (type IV) has been associated with a high survival rate of dental implants [1,18]. However, there are few studies that have evaluated the biomechanical behavior of surface-treated versus machined surface implants [19,20].

In this context, biomechanical studies offer substantial information, since they may indicate a parameter for situations involving low-density bone (types III and IV) in conjunction with different dental implant designs and surface treatments. Thus, the aim of this study is to

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assess the effect of different dental implant designs (i.e., an external hexagon with a standard platform, an external hexagon with platform switching, and Morse taper), bone types (III and IV), loading (axial and oblique), and surface treatment (treated and machined) on the stress distribution around an implant by using the 3D finite-element method. The study hypotheses are as follows: 1) dental implants (Ø 5 mm) with a platform-switching concept show stress distribution on the cortical bone around an implant that is similar to external hexagon implants (Ø 5 mm). 2) Morse taper implants show the best stress distribution on the cortical bone around an implant. 3) Dental implants placed in type IV bone show the largest area of stress concentration in comparison to dental implants placed in type III bone. 4) Surface-treated dental implants show the best stress distribution on cortical bone compared to machined surface implants.

2. Material and methods

2.1. Experimental design

This research was developed by considering four factors of study: the dental implant design (an external hexagon with a standard platform or an external hexagon with platform switching and a Morse taper), bone types (III and IV), surface treatment (treated and machined), and loading (axial and oblique).

2.2. Three-dimensional design and FE analysis scenarios

This methodology follows previous studies [2,4,21]. Twelve 3D models were developed (Table 1), thus representing a section of mandibular bone of the second molar region with an implant and single-unit crown.

The geometry of the bone tissue, a region of mandibular bone with a dental implant and implant-supported crown, was obtained by the decomposition of computed tomography through the use of InVesalius® software (CTI, Campinas, São Paulo, Brazil) and simplified in the Rhinoceros 4.0 software (Seattle, WA, USA), which was modeled via trabecular bone in the center, surrounded by a 1 mm layer of cortical bone. The implant design was obtained by simplifying two original dental implants within the Conexão® System (Conexão Sistemas de Prótese Ltda., Arujá, SP, Brazil), an external hexagon and Morse taper, with dimensions of 10 × 5 mm. All implants and abutments were simplified by SolidWorks 2010 software (SolidWorks Corp, Concord, MA, USA) and Rhinoceros 4.1 (Seattle, WA, USA). The crown was modeled with a 10 mm height; it was screwed in the external hexagon and platform-switching models and cemented in the Morse taper model. The design of the crown surface was digitized from 1 artificial second mandibular molar (Odontofix Industria e Comercial de Material Odontologico Ltda., Ribeirão Preto, SP, Brazil). The occlusal lining material used was feldsphatic porcelain, and a nickel-chromium alloy was used for crown framework [4,22].

Table 1
Model description.

Implant	Surface	Bone type	Design	Model
Implant (5 × 10 mm)	Machined	III	External hexagon	Model 1 (M)
			Platform switching	Model 2 (MM2)
			Morse taper	Model 3 (3M)
		IV	External hexagon	Model 4 (M)
			Platform switching	Model 5 (M)
			Morse taper	Model 6 (M)
	Treated	III	External hexagon	Model 7 (M)
			Platform switching	Model 8 (M)
			Morse taper	Model 9 (M)
		IV	External hexagon	Model 10 (ML)
			Platform switching	Model 11 (M11)
			Morse taper	Model 12 (M12)

The implant surface modeling was performed by simulating bonded contact on all implant faces and bone tissue. The drawing of the implant and simplification was conducted using 2010 SolidWorks software (SolidWorks Corp., Waltham, MA, USA) [21]. The machined surface was considered a flat contact surface between the bone tissue and implant, according to previous studies [2,4,21]. The surface treatment was considered in 4 different regions of the implant (mesial, distal, buccal, and lingual). The development of a surface area increase of approximately 57% of the original area was considered on each of the faces that were analyzed. The surface-area increase was obtained through modeling the spherical surfaces in the region of the implant platform, consistent with the cortical bone, which was elaborated with 16 spherical (diameter: 95 μm; radius: 47.5 μm; surface area of 1 hemisphere in contact with bone tissue: 14,169 μm^2) in each implant surface, according to other studies that were previously conducted [23,24].

After completion of the modeling, the finite-element software FEMAP 10.2 (Siemens PLM Software Inc., Santa Ana, CA, USA) was used to create finite-element models in the pre-processing stages. Thus, all meshes were generated by using tetrahedral parabolic solid elements.

All mechanical properties of each simulated material were attributed to the meshes by using literature values, according to Table 2 [16, 25–27] In order to analyze the type III bone and type IV bone, the modulus of elasticity of the type IV trabecular bone was modified [16]. All materials were considered isotropic, homogeneous, and linearly elastic.

Symmetric welds were simulated for all contacts, with the exception of the abutment/implant contact in the external hexagon and crown/abutment, which was simulated by symmetric contact. The boundary conditions were fixed in all axes (x, y, and z) at both bone-block sections (anterior and posterior faces). All of the other model parts were under free restrictions. The applied force was 200 N axially (50 N at each cusp tip) and 100 N obliquely (50 N at each lingual cusp tip). Functional load was applied perpendicular to the chewing surfaces of the cusp [21].

Then, the finite element analysis was generated in the FEMAP 10.2 software and exported for mathematical calculation in the NeiNastran 11.0 software (Noran Engineering, Inc., Westminster, CA, USA), which was run on a workstation (HP Z200, Hewlett-Packard Company, Palo Alto, CA, USA) on which finite-element mesh for implants with a machined surface (Fig. 1a–c) and a treated surface (Fig. 1d–g) were generated. The results were imported again into the FEMAP 10.2 software for viewing and the post-processing of the maximum principal stress and microstrain maps. The levels of maximum principal stress and microstrain were analyzed in the cortical bone and measured in the mesial, distal, buccal, and lingual regions around each dental implant. The solid mesh convergence error showed the highest value for cortical bone in model 7 being less than 0.076 (7.1%).

2.3. Analysis of stress criteria

The value of maximum principal stress was used as a criterion for stress analysis on bone tissue, since the use of this analysis is recommended for the compression and traction of friable materials. [2,21, 28]. The microstrain analysis (μStrain) [29] on bone tissue was used in order to allow a comparative analysis with maximum principal stress. The unit of measurement was the Megapascal (MPa) for maximum principal stress and μStrain (με) for the microstrain analysis of bone tissue.

Table 2
Mechanical properties.

	Modulus of elasticity (E) (GPa: gigapascals)	Poisson's ratio (μ)	References
Type III bone	1.3	0.30	Sevimay et al. [16]
Type IV bone	1.1	0.30	Sevimay et al. [16]
Cortical bone	13.7	0.30	Sertgoz [25]
Titanium (implant)	110.0	0.35	Benzing et al. [26]
Nicer alloy	206.0	0.33	Anus vice [27]
Feldspathic porcelain	82.8	0.35	Sertgoz [25]
Zinc phosphate cement	22.4	0.35	Anusavice [27]

A detailed analysis of the structure of the cortical bone was performed for all models that were studied, including analysis of the maximum principal stress and bone microstrain. This cortical bone was selected because of its relevance to implantology, since this region accumulates the highest stress concentration in the bone tissue and provides an important biological function for the longevity of dental implants, as discussed in previous studies [2]; the microstrain analysis criterion was established in Frost's mechanostat theory [2,21,28].

2.4. Statistical analysis

The effect of the type of loading (axial or oblique) was analyzed by three-way ANOVA regarding loading, models, and surface. The different types of bone tissue were analyzed by two-way ANOVA—models and bone type. The effect of different surface treatments was analyzed by three-way ANOVA—model, surface, and bone type—for each type of loading and surface simulated. All tests were performed by using values of maximum principal stress and bone microstrain. Values of $p < 0.05$ were considered to be statistically significant. Tukey's post-hoc test was used to analyze interactions between results. Sigma Plot 12.3 (Systat Software Inc., San Jose, CA, USA) performed all statistical analyses.

3. Results

3.1. Loading

The loading analysis showed that oblique loading increased the area of stress concentration ($p < 0.001$) and microstrain ($p < 0.001$) on the bone tissue compared to axial loading, as observed in Fig. 2a–b (maximum principal stress) and c–d (microstrain).

3.2. Implant design

The maximum principal stress showed that there were no significant differences in the stress distribution among the models under axial loading ($p > 0.05$; power of the test: $\alpha = 0.871$) or oblique load (Figs. 2b and 3a); the Morse taper exhibited the lowest magnitude of stresses compared to the external hexagon with a standard platform ($p < 0.05$) and the external hexagon with platform switching ($p < 0.05$). The models with platform switching did not appear to be statistically significant in comparison to a standard platform ($p > 0.05$).

The bone-microstrain analysis showed that the Morse taper exhibited the lowest magnitude of microstrain compared to an external hexagon with platform switching ($p < 0.05$) and an external hexagon with a standard platform ($p < 0.001$) for both loadings. The external hexagon with platform switching exhibited the lowest magnitude of microstrain compared to the external hexagon with a standard platform ($p < 0.001$), as shown in Fig. 3b. The highest magnitude values of microstrain and stress were observed under oblique loading.

3.3. Bone types

The maximum principal stress showed that there were no significant differences between the bone types (III and IV) and machined and treated surfaces in the magnitude of stress on the cortical bone ($p > 0.05$) under axial (Fig. 4a) and oblique loading (Fig. 4b).

The bone-microstrain analysis showed that, type IV bone increased the levels of bone microstrain, under an axial load and for an implant with a machined surface ($p = 0.047$), according to Fig. 4c. However, under oblique loading, there were no significant differences between the different bone types, regardless of the type of surface ($p > 0.05$), as shown in Fig. 4d.

3.4. Surface treatment

The maximum principal stress showed that type IV bone increased the levels of bone microstrain in the analyzed regions of the cortical bone under axial loading ($p < 0.001$) for all models. Under oblique loading, the surface treatment did not significantly modify ($p = 0.139$) the stress concentration around the implant. However, there was a decrease of the mean intensity of the stress concentration on bone tissue when compared to the implants with a machined (mean = 2.184 MPa) or

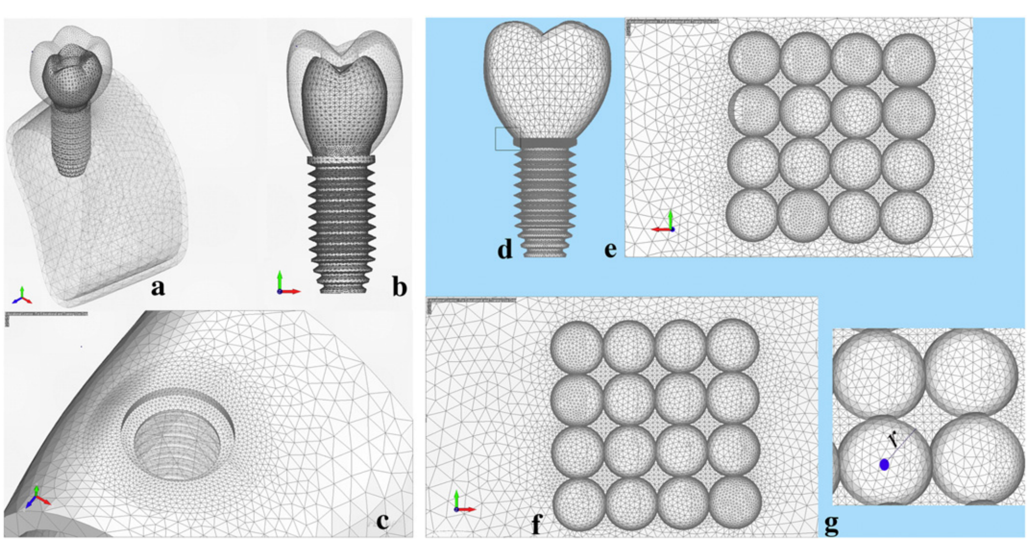


Fig. 1. Finite element mesh. Scheme for external hexagon with platform switching model and bone tissue (a); external hexagon with platform switching and a crown (b); and cortical bone, superior view (c). Finite element mesh. Scheme for external hexagon with a standard platform model (d); detail of the regions with a treated surface, an implant surface with a microsphere (e), and a cortical bone tissue surface showing the region of surface modification (f); and zoom of the specific region of the microspheres showing a defined radius: r: 47.5 μm (g).

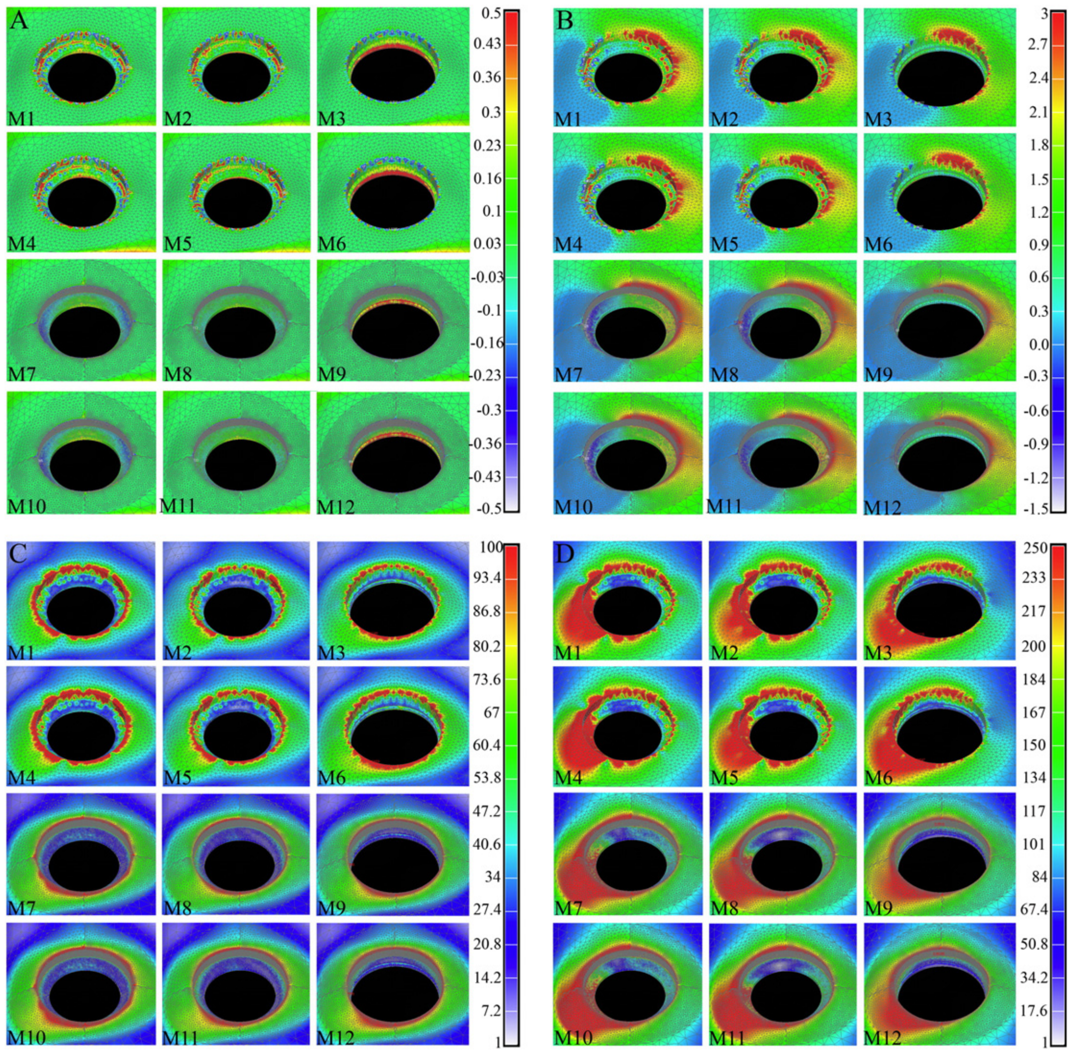


Fig. 2. Superior view of the cortical bone: a—axial loading (maximum principal stress: MPa); b—oblique loading (maximum principal stress: MPa); c—axial loading. (microstrain—με); and d—oblique loading (microstrain—με).

treated surface (mean = 1.887 MPa), as can be seen in detail for each model in Table 3.

Fig. 5a and b shows maps of maximum principal stress for the different faces that were analyzed under oblique loading for the models of implants with machined (Fig. 5a) and treated surfaces (Fig. 5b) for type IV bone (models 4–6: machined surface; models 9–12: treated surface). Under oblique loading, it can be observed that the models of a treated surface increased the area of stress distribution (Fig. 5b) compared to the models of the machined surface. Moreover, the Morse taper showed the best pattern of stress distribution in both surface-treatment situations compared to other models. This tendency was also persistent for the other models presented.

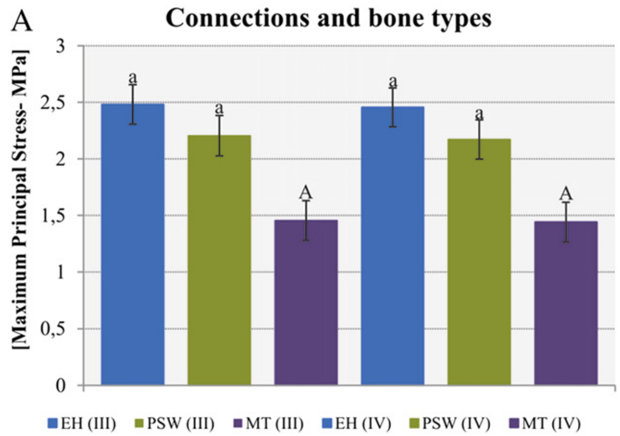
The bone-microstrain analysis showed that, under axial loading, the treated surface increased the areas and magnitude of microstrain around the implant ($p < 0.001$) for all of the models (Table 4) and also increased the areas and magnitude of bone microstrain ($p < 0.001$) for the implants of a treated surface (mean = 349.196 με) compared to implants of the machined surface (mean = 296.513 με) under oblique loading.

4. Discussion

The hypotheses in this study proposed in relation to the analyzed dental implant designs were partially accepted because the external hexagon with platform switching and the external hexagon with a standard platform showed a pattern of stress distribution similar to the bone tissue using the maximum principal stress criterion. However, in terms of the bone-microstrain criterion, the platform-switching implants were more effective than the implants that consisted of an external hexagon with a standard platform under oblique loading. These findings agree with other studies in the literature [30–35] that evaluated the similarity [31] or relative advantage of the platform-switching concept [30,33–35] in the results of the stress distribution around an implant.

The Morse taper design exhibited the best biomechanical performance of all of the analyzed situations. Under oblique loading, this design decreased the magnitude of the maximum principal stress by approximately 35% and of microstrain by 43% compared to the external hexagon design with a standard platform.

Indeed, literature has consistently reported the effectiveness of the Morse taper design. Studies have demonstrated a better biomechanical performance of Morse taper design in comparison to an external hexagonal implant [2,36]. This is possibly associated with a drive-shaft force that is located closer to the center of the implant, which promotes stress distribution along the implant and decreases the micro-movement in the screws and abutments of the system [37]. Furthermore, the fact that the Morse taper exhibits a line of cementation may have favored stress and microstrain dissipations on the bone tissue, as was reported in a previous study [2].



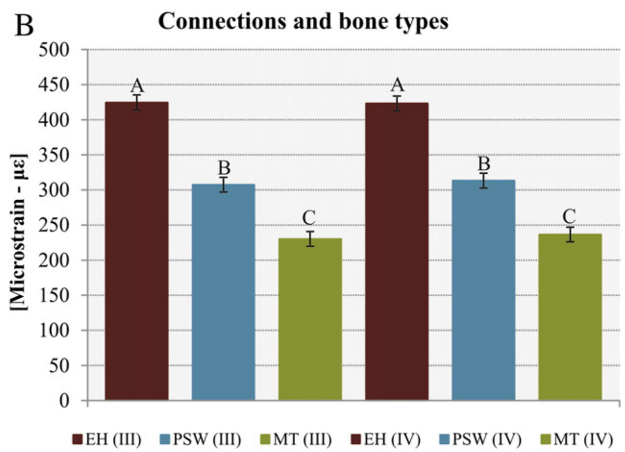


Fig. 3. a: average maximum principal stress for the different models analyzed. Uppercase/lowercase letters (A/a) presented $p < 0.05$ and, similar letters lowercase (a,a) presented $p > 0.05$, oblique loading; b: analysis of bone microstrain for different models that were analyzed. Different uppercase letters (A,B; A,C; B,C) presented $p < 0.05$ and, similar uppercase letters (A,A; B,B; C,C) presented $p > 0.05$, oblique loading.: IE: external hexagon; PSW: Platform Switching; MT: Morse taper; III: type III bone; IV: type IV bone.

Regarding the different bone types that were analyzed, we observed that in only 1 analysis—microstrain criterion (με) and axial loading—the type IV bone was statistically harmful for stress distribution in comparison to type III bone; in the other analyses, there was no significant difference. Therefore, the hypothesis was partially accepted. Through finite-element methods, other studies have indicated an increase in stress within low-density [15,16] or osteoporotic bone [12] compared to bone tissue of better density. Another factor that could interfere with our result is the same cortical bone thickness between type III bone and type IV bone. Okumura et al. [13] indicated that the reduction of the cortical bone thickness increased the stress concentration. Therefore, the constant thickness could have had a protective effect that masked the effect of the lower modulus of elasticity employed for type IV bone.

In an analysis of the effect of the different dental implant designs and bone types, our results showed that, for type IV bone, the Morse taper was more effective than the external hexagon. These results are in agreement with Lin et al.'s [38] study using finite-element methods, which indicated that, in a low-density-type bone, the Morse taper design behaved more favorably than the external hexagon design.

Furthermore, other biomechanical variables have been indicated as important. Li et al. [14] using the method of finite 3D elements, indicated that implants with greater length represent an important variable for type IV bone. Concordant results were presented by Tada et al. [15], which also emphasized the use of greater-length implants in type IV bone. In this way, the use of a large-diameter (5 mm) and regular-length (10 mm) implant had acted effectively in terms of the stress distribution in both bone types that were analyzed.

The systematic-review study has indicated that the survival rate of implants placed in normal-density bone is greater than in low-density bone [1]. In our study, Young's modulus of trabecular bone tissue was modified in order to simulate low-density bone (type III: 1.3 GPa; type IV: 1.1 GPa) according to the literature [16]. A possible limitation of the bone tissue that was used is related to the architecture of the trabecular bone and cortical bone thickness [15]. In our study, the trabecular bone tissue was simplified in order to facilitate modeling. This may explain the stress/strain results, which did not show a significant difference in the pattern of stress distribution.

Our results showed a higher stress concentration under oblique loading. These data are in agreement with the literature, which indicates that lateral and oblique loadings are the most harmful to the implant structure and the bone tissue around the implant [2,4,21]. Thus, it is important that a meticulous occlusal adjustment in oral rehabilitation with implant prostheses be supported, since in oblique loading, conditions associated with other risk factors, such as bruxism, can induce the failure of dental implants [4].

Regarding the proposed surface treatment, there was a significant increase of the stress/strain concentration on the cortical bone tissue. It is understood that the transmission of stresses arising from occlusal loading occurs in the regions of the interfaces' contact with the bone/implant; the smaller the area of bone contact, the greater the possibility of an overload in the region [16]. Therefore, the magnification of the surface area of these regions allowed a larger propagation and stress dissipation around the cortical bone. Consequently, the study's proposed hypothesis was rejected. In this context, the cortical bone tissue shows a modulus of elasticity that is 10 times greater than the trabecular bone tissue, which makes it resistant to deformation [16,39]. Thus, the increase of the area of the implant/bone contact in the cortical bone spreads a larger stress/strain in this region. Further, a reduction in bone density (type IV) showed a trend of increasing the stresses/strains (Table 4).

Surface treatment is one relevant factor for the survival of the dental implant [1], but there are few biomechanical studies about treated surfaces [23,24,40,41]. This study simulated a geometrical modification of the implant surface in which the surface treatment of the implants in the cortical bone was observed to increase the stress dissipation in this region. Similarly, other studies using finite-element methods indicated that the use of a treated surface increased the area of stress distribution when compared to a machined surface [23,24,40,41].

It is noteworthy that a higher magnitude of maximum principal stress and microstrain in the cortical bone was observed in the models of a treated surface ($p < 0.05$), except during the condition of oblique loading of the maximum principal stress. These data are consistent with studies of finite elements, which have indicated the amplification of the magnitude of stresses in the cortical bone region [19,20,42]; however, there are reports that the increase of stress in the cortical region resulted in a reduction of the maximum stresses in the trabecular bone region [20,43]. Significant changes in the distribution of stresses in trabecular bone tissue were not observed in this study.

A relevant finding was noted in the condition of axial loading; our results indicated that there was an increase in the area and magnitude of stress/strain in the region around the implant. The literature has indicated satisfactory results for the biomechanical behavior, considering that, under axial loading, the increase in magnitude of stress in the cortical bone can reduce bone loss due to disuse/bone atrophy [44]. Other studies that only modified the coefficient of friction to simulate the effect of a treated surface also showed an increase of stresses in the bone crest of surface-treated implants [19,20]. However, one of the great advantages of our study was the modeling of a surface with a larger contact area, rather than just changing mechanical properties.

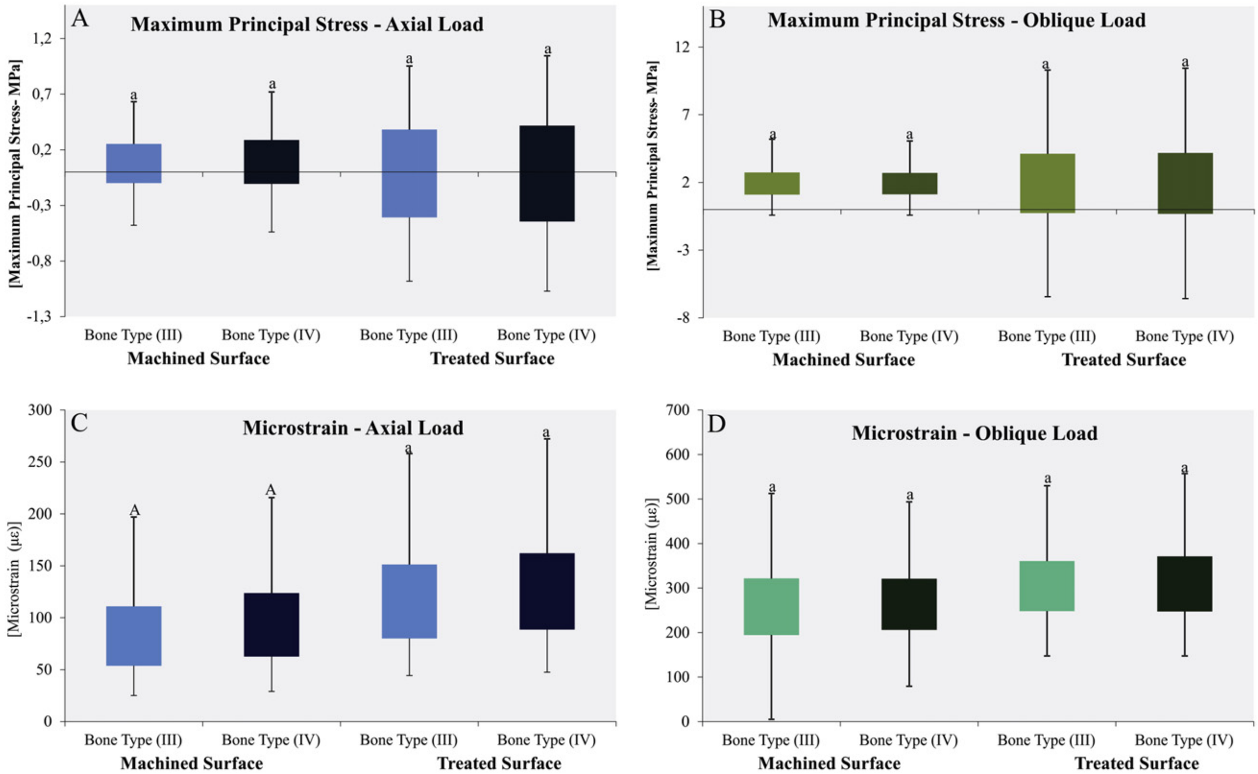


Fig. 4. Maximum principal stress analysis: a—axial loading; b—oblique loading; microstrain analysis: c—axial loading; and d—oblique loading. Similar lowercase letters (a,a) presented $p > 0.05$, similar uppercase letters (A,A) presented $p < 0.05$. Type III bone and type IV bone.

Furthermore, under axial loading, it is noteworthy that the surface treatment conducted a change in the direction of load application, which predominantly emerged from traction stress to compressive stress in the region around the implant (Table 3; Fig. 2a). This fact is very beneficial, considering that the bone tissue can support a higher intensity of compressive stress when compared to tensile stresses [28].

Table 3
Maximum principal analysis in the bone tissue for different situations.

Loading	Surface	Implant design	Bone type	Mean of stress (MPa)	Standard deviation
Axial	Machined	External hexagon	III	0.0589	0.3398
			IV	0.0623	0.3734
		Platform switching	III	0.0275	0.2498
			IV	0.0379	0.2863
		Morse taper	III	−0.0210	0.1933
			IV	−0.0264	0.2219
	Treated	External hexagon	III	−0.273	0.5244
			IV	−0.292	0.5586
		Platform switching	III	−0.176	0.2205
			IV	−0.173	0.2197
		Morse taper	III	−0.239	0.2044
			IV	−0.272	0.2235
Oblique	Machined	External hexagon	III	2.492	2.186
			IV	2.439	2.137
		Platform switching	III	2.487	2.244
			IV	2.522	2.211
		Morse taper	III	1.583	1.141
			IV	1.582	1.162
	Treated	External hexagon	III	2.472	4.929
			IV	2.473	4.933
		Platform switching	III	1.921	2.199
			IV	1.823	4.933
		Morse taper	III	1.330	1.916
			IV	1.301	1.933

This way, the increase of maximum principal stress and micro-strain under axial loading can be analyzed as an improvement in the physiological behavior of bone tissue [45]. Hansson [45] indicated that implants with a treated surface can increase the magnitude of stresses in the cortical bone under axial loading, and this situation can be beneficial, since the bone tissue supports threshold stress higher than the values identified in the treated surface, thus indicating that stimulation of the cortical bone under axial loading of a machined surface by compressive stresses is insufficient to preserve the bone tissue around an implant. Use of the treated implant surface will mechanically stimulate loading and stress distribution in the region. Indeed, a significant increase in the magnitude of stresses under axial loading in implants with a treated surface (mean = 0.238 MPa), in comparison to a machined surface (mean = 0.02 MPa), was observed.

Consequently, it may be a dilemma to adopt a treated surface that can promote a faster and more efficient osseointegration process in the region of the cortical bone, since it may simultaneously increase the level of stress in the cortical-bone interface; however, it is understood that the increase in the stress-controlled level can stimulate the maintenance of osseointegration [43]. In this respect, the maximum levels of stress (oblique loading, treated-surface mean of 1.887 MPa; machined-surface mean of 2.184 MPa) and strain (oblique loading, treated-surface mean of 349.196 με; machined-surface mean of 296.513 με) analyzed in this region of cortical bone are compatible with physiological values established in the literature of 72–76 MPa traction stress and 140–170 MPa compressive stress, [46], and, further, are compatible with values of bone microstrain acceptable for bone tissue [29]. With respect to bone microstrain, according to Frost's mechanostat theory, in order to maintain suitable conditions, bone-microstrain values should not exceed 3000 με (overload) or be less than 50–100 με (resorption/disuse) [29,47]; thus, bone-deformation values are within physiological parameters.

In contrast to this study, which changed the geometry conditions of the finite-element mesh, some studies have considered the surface

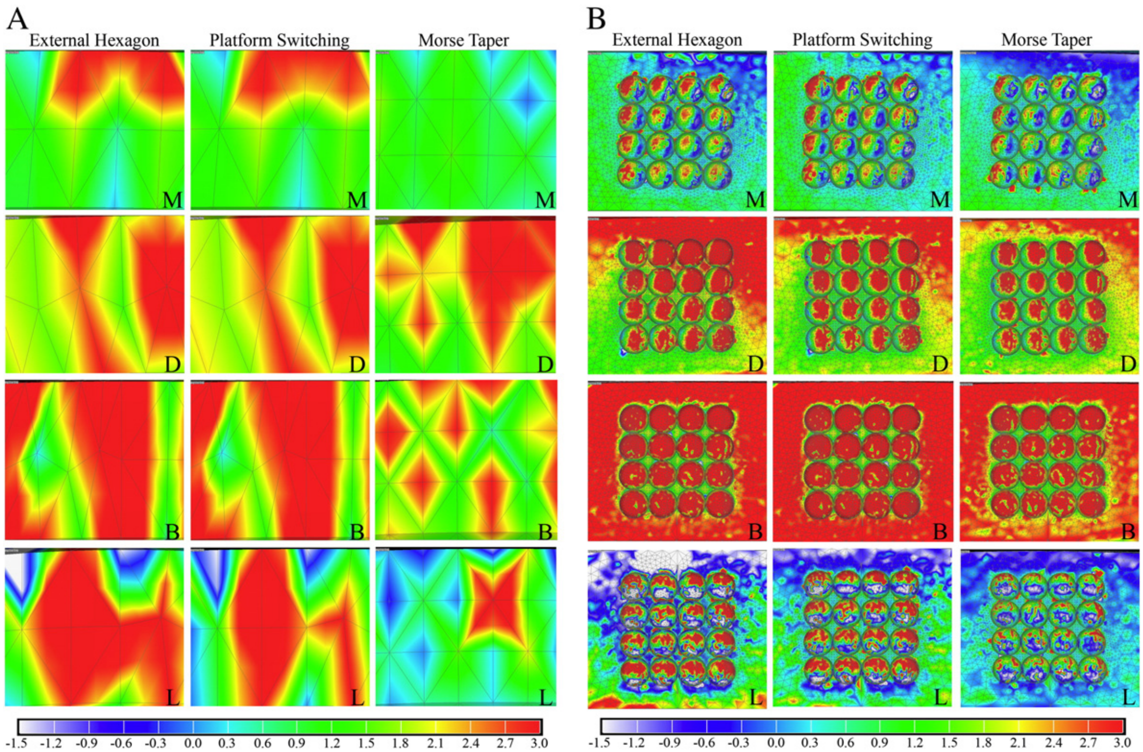


Fig. 5. a: view of machined surface regions around an implant in cortical bone. b: view of treated surface regions around an implant in cortical bone. Oblique loading. Maximum principal stress (MPa). M: mesial; D: distal; B: buccal; L: lingual. Type IV bone (a: M to M; b: M to MM2).

treatment by only simulating the change of the coefficient of friction within the implant/bone tissue [19,20,43]. Such research has shown similar results to our study (i.e., increasing the magnitude of stresses in the cortical bone). Our study showed a difference from previous studies [19,20,43] because the provision of a change in the geometry of the implant allowed for an increased bone-contact surface.

Table 4
Microstrain analysis in the bone tissue for different situations.

Loading	Surface	Implant design	Bone type	Mean of microstrain (με)	Standard deviation
Axial	Machined	External	III	109.668	61.687
		hexagon	IV	119.369	69.11
		Platform	III	80.917	42.80
		switching	IV	95.410	49.78
		Morse taper	III	73.403	22.833
			IV	84.551	26.279
	Treated	External	III	179.767	73.478
		hexagon	IV	187.454	74.614
		Platform	III	105.346	38.809
		switching	IV	116.226	49.782
		Morse taper	III	101.929	53.428
			IV	106.980	32.267
Oblique	Machined	External	III	360.428	243.000
		hexagon	IV	366.086	245.150
		Platform	III	312.501	163.009
		switching	IV	318.375	164.371
		Morse taper	III	205.699	82.054
			IV	215.989	84.620
	Treated	External	III	488.303	256.594
		hexagon	IV	480.205	262.568
		Platform	III	302.590	61.766
		switching	IV	308.201	64.928
		Morse taper	III	254.550	48.580
			IV	261.327	52.526

The surface modification of implants is recommended because it enlarges the area of bone contact [1], thus allowing better resistance to shear forces due to the increased friction coefficient [19]. However, the literature suggests that an increase of stresses in the cortical bone, with the increase of the surface roughness in this region [20], must be properly evaluated in order to prevent bone loss around the implant.

The main limitations of the study are related to the constraints of a computer simulation [2,21]. Our study considered linearly elastic, isotropic, and homogeneous material properties. Future studies should use the concept of non-linear analysis and an anisotropic bone. However, within the conditions of the study, the finite-element method shows advantages because it allows an analysis of the internal structures of bone tissue and implant-supported prostheses. It presents an advantage when compared with other methodologies, but clinical studies must evaluate the benefits of the biomechanical variables that are analyzed in this study.

Finally, the results indicate the superiority of the Morse taper design in stress distribution and implants, as the concept of a switching platform did not reveal biomechanical disadvantages in comparison to an external hexagon with a standard platform. Therefore, biologically, the conditions of better bone preservation around the implant with the use of a Morse taper design and platform switching endorse the use of these systems [7,36] in comparison to an external hexagon with a standard platform [7].

Furthermore, increasing the surface area of the implants with the treated surface did not harm the stress distribution to non-physiological levels. Therefore, clinical [48] and review studies [1,49] endorse the benefits of a treated surface, mainly for low-density bone (type IV); thus, we believe in the biomechanical viability of these treated surfaces in comparison to machined surfaces. Randomized controlled trials must consider the longevity outcome of peri-implant bone loss, the survival of implants with surface treatment, and different types of connections, as well as possible complications of implant-supported prostheses, especially in terms of fixation screws.

5. Conclusion

Based on the methodology used and the results obtained, the following can be concluded:

- The Morse taper design showed better biomechanical behavior independent of the type of analysis.
- An external hexagon with platform switching was more favorable than an external hexagon with a standard platform.
- The different bone types that were analyzed indeed indicated a significant difference in the distribution of stresses/strains.
- Surface treatment increased the area of stress/strain concentration on the cortical bone.
- Oblique loading was more harmful to the stress distribution than axial loading.

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