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Biomechanical analysis of different implant-abutments interfaces in different bone types: An in silico analysis

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ABSTRACT

The purpose of this study was to analyze the stress distribution of bone tissue around implants with different implant-abutment interfaces: platform switching (PSW); external hexagon (EH) and Morse taper (MT) with different diameters (regular: Ø 4 mm and wide: Ø 5 mm), bone types (I–IV) and subjected to axial and oblique load conditions using three-dimensional finite element analysis (3D-FEA). Sixteen 3D models of various configurations were simulated using InVesalius, Rhinoceros 3D 4.0, and SolidWorks 2011 software, and processed using Femap 11.2 and NeiNastran 11.0 programs. Axial and oblique forces of 200 N and 100 N, respectively, applied at the occlusal surface of prostheses. Maximum principal stress values were obtained from the peri-implant cortical bone of each model. Statistical analyses were performed using ANOVA and Tukey's test for maximum principal stress values. Oblique loading showed higher tensile stress than axial loading ($P < 0.001$). Wide-diameter implants showed lower stress concentration rather than regular-diameter implants, regardless of both connection and bone type ($P < 0.001$). Under axial loading, wide-diameter EH implants with regular platforms showed more favorable stress distribution than PSW implants for axial loading ($P < 0.001$); however, under oblique loading, PSW implants exhibited lower stress concentrations ($P < 0.001$). Regular-diameter MT implants showed lower stress than EH implants ($P < 0.001$). Bone type IV showed higher stress in the cortical region than bone types I and II ($P < 0.001$), but no significant difference when compared with bone type III ($P > 0.05$). The conclusion drawn from this in silico is that MT implants should be considered for use in situations that preclude the placement of wide-diameter implants, particularly where bone types III and IV are concerned.

1. Introduction

Preserving the bone level around implants is considered an important challenge in implant dentistry [1]. Reports indicate that implant survival may be compromised by external factors - such as apical migration of peri-implant tissues and local bacterial colonization - that have been associated with an increased risk for bone resorption and subsequent rehabilitation failure [2].

In view of this, platform switching (PSW) concept has been considered as an alternative means of reducing marginal bone loss around the implants [3]. The PSW concept refers to selection of a reduced prosthetic platform in relation to implant diameter, thereby increasing the horizontal distance between the abutment-implant interface and bone tissue [4]. While some studies have attributed this influence due

to the stress distribution in the long axis of the PSW implants [3], implant diameter is considered the more influential variable [5].

Bone tissue quality and quantity are also believed to directly influence stress distribution [6]. Some studies report low-density bone tissue to have limited stress tolerance and an increased risk for bone resorption [7]. Clinically, low-density bone is associated with reduced implant survival rates compared to those bone of normal-density [8]. With other biomechanical studies having found no correlation between bone density and stress distribution, however, consensus remains unresolved [3,9].

Morse taper (MT) implants incorporating PSW concept show better stress distribution than implants with external connections [1,3]. However, there is no consensus regarding whether regular-diameter MT implants are comparable to wide-diameter external hexagon (EH)

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Table 1
Models description.

Models	Bone type	Description
M1	I	EH – Ø 5 × 10 mm with UCLA 4 mm (PSW)
M2		EH – Ø 5 × 10 mm with UCLA 5 mm
M3		EH – Ø 4 × 10 mm with UCLA 4 mm
M4		MT – Ø 4 × 10 mm with Pilar Speed
M5	II	EH – Ø 5 × 10 mm with UCLA 4 mm (PSW)
M6		EH – Ø 5 × 10 mm with UCLA 5 mm
M7		EH – Ø 4 × 10 mm with UCLA 4 mm
M8		MT – Ø 4 × 10 mm with Pilar Speed
M9	III	EH – Ø 5 × 10 mm with UCLA 4 mm (PSW)
M10		EH – Ø 5 × 10 mm with UCLA 5 mm
M11		EH – Ø 4 × 10 mm with UCLA 4 mm
M12		MT – Ø 4 × 10 mm with Pilar Speed
M13	IV	EH – Ø 5 × 10 mm with UCLA 4 mm (PSW)
M14		EH – Ø 5 × 10 mm with UCLA 5 mm
M15		EH – Ø 4 × 10 mm with UCLA 4 mm
M16		MT – Ø 4 × 10 mm with Pilar Speed

implants in terms of stress distribution. Thus, the aim of this study was to evaluate the biomechanical behavior of different implant-abutment interfaces in relation to implant diameter (regular and wide) and bone tissue type (I–IV). The null hypotheses were as follows: (1) the implant diameter did not influence stress distribution in the cortical bone tissue, (2) the implant-abutment connection did not influence stress distribution in the cortical bone tissue, and (3) the quality of bone tissue did not influence stress concentration in the cortical bone tissue.

2. Material and methods

2.1. In silico experimental design

This research was designed to consider three variable factors: 1) diameter (Ø 4 and Ø 5 mm); 2) implant-abutment interface (EH, MT, and PSW), and 3) bone tissue type (I–IV). Sixteen models were created to test these factors under axial and oblique loading (Table 1).

2.2. Three-dimensional and finite-element analysis

This methodology follows protocols from previous studies [1,3]. In silico three dimensional finite-element models were created to represent a mandibular bone section from the second molar region. Modeling was based on sagittal computerized tomography and accomplished using InVesalius software (CTI Renato Archer, Campinas, SP, Brazil). Surface simplification was performed using Rhinoceros 4.0 software (NURBS Modeling for Windows, Seattle, WA, USA). Different bone tissues were simulated according to the Lekholm and Zarb classification for the bone tissue [10]: type I, consisting of cortical bone only; type II, consisting of a 2-mm cortical layer and trabecular bone of normal density; type III consisting of a 1-mm cortical layer and trabecular bone of normal density; and type IV, consisting of a 1-mm cortical layer and trabecular bone of low density.

Implant and abutment was obtained from a version of the original connection (Conexão Sistemas de Prótese Ltda, Aruja, SP, Brazil), and simplified using SolidWorks 2010 (SolidWorks Corp, Concord, MA, USA) and Rhinoceros 4.0 software. Each bone model was fitted with either an EH implant and UCLA abutment or MT implant with solid abutment. Implants were 10 mm in length and either Ø 4.0 or Ø 5.0 mm in diameter (Fig. 1). The implant-supported crown was simulated with a screw-retained system for EH implant models, while MT models employed a cement-retained system with a cement layer thickness of 0.08-mm. Crowns were modeled on an artificial second molar tooth were simulated using a 3D scanner (MDX-20w, Roland DG, SP, Brazil) for digitalization (Odontofix Industria e Comercio de Material Odontologico Ltda., Ribeirao Preto, SP, Brazil). Feldspathic porcelain was used as the veneering material on external crown surfaces, and a

nickel–chromium alloy was used of the framework.

After the modeling phase, all geometries were exported to finite-element analysis software FEMAP 11.2 (Siemens PLM Software Inc., Santa Ana, CA, USA) for pre- and post-processing. FEMAP was used to create finite element models from meshes of tetrahedral parabolic solid elements. The mechanical properties of each simulated material were determined according to previously published studies (Table 2) [11,12]. All materials were considered isotropic, homogeneous, and linearly elastic.

The crown-abutment and abutment-implant interfaces were assumed to have symmetrical contacts, and all other contacts were also assumed to be symmetrically welded. Constraint conditions were fixed in all axes (x, y, and z) at the anterior and posterior surfaces of each bone sections. All of the other model parts were unrestricted. A force of 200 N was distributed axially at four points on the internal slope of each cusps, and 100 N was distributed obliquely at two points on the internal slope of the lingual cusps (Fig. 1). Functional load was applied perpendicularly to the chewing surfaces of the cusps [1,3].

After the pre-processing in FEMAP 11.2 software, the models were exported for mathematical calculation in the NeiNastran 11.0 software package (Noran Engineering, Westminster, CA, USA). With analytical problems solving complete, the models were then imported to FEMAP 11.2 for post-processing and visualization of stress maps. Maximum principal stress analysis was used to identify traction and compression stresses in peri-implant cortical bone due to the friable nature of the tissue. Measurement was in mega-Pascal (MPa) units, and tensile and compressive stresses were distinguishable by positive and negative values, respectively.

2.3. Statistical analysis

The highest 50 values for elements of maximum principal stress in peri-implant cortical bone [13] were compiled in Excel (Microsoft Office Excel, Redmond, WA, USA) and the spreadsheets exported to Sigma Plot 12.0 software package (Systat Software Inc., San Jose, CA, USA). Data were analyzed for normality (test Shapiro-Wilk test) and equal variance, before being subject to analysis of variance (ANOVA). Two-way ANOVA was conducted on diameter versus bone type, and abutment-implant interface versus bone type, under axial and oblique loading. Regions (mesial, buccal, lingual, and distal) and loading (axial and oblique) were analyzed using three-way ANOVA (connection, loading, and region). The Tukey post hoc test was used to identify differences between groups with significance set at $P < 0.05$.

3. Results

3.1. Diameter analysis

Under axial loading, regular-diameter implants (Ø 4 mm) showed higher compressive stress (mean: 1.324 MPa) than those wide-diameter (Ø 5 mm) implants (mean: 0.636 MPa) ($P < 0.001$). In bone type I, lower stress concentrations without significant influence of diameter ($P = 0.553$) were observed; however, in the other bone types the wide-diameter contributed to stress distribution more than the regular-diameter ($P < 0.001$) (Fig. 2). Under oblique loading, wide-diameter implants showed lower tensile and compressive stresses (mean: 3.078 MPa) than the regular-diameter implants (mean: 9.773 MPa), regardless of both connection and bone type ($P < 0.001$) (Fig. 3).

3.2. Implant-abutment interfaces analysis

Maximum principal stress analysis revealed that regular-diameter MT implants show lower tensile stress than EH implants under both loadings ($P < 0.001$); Wide-diameter EH implants exhibited lower stress concentration than PSW implants under axial loading ($P < 0.001$) (Figs. 2 and 4). Under oblique loading, however, the PSW
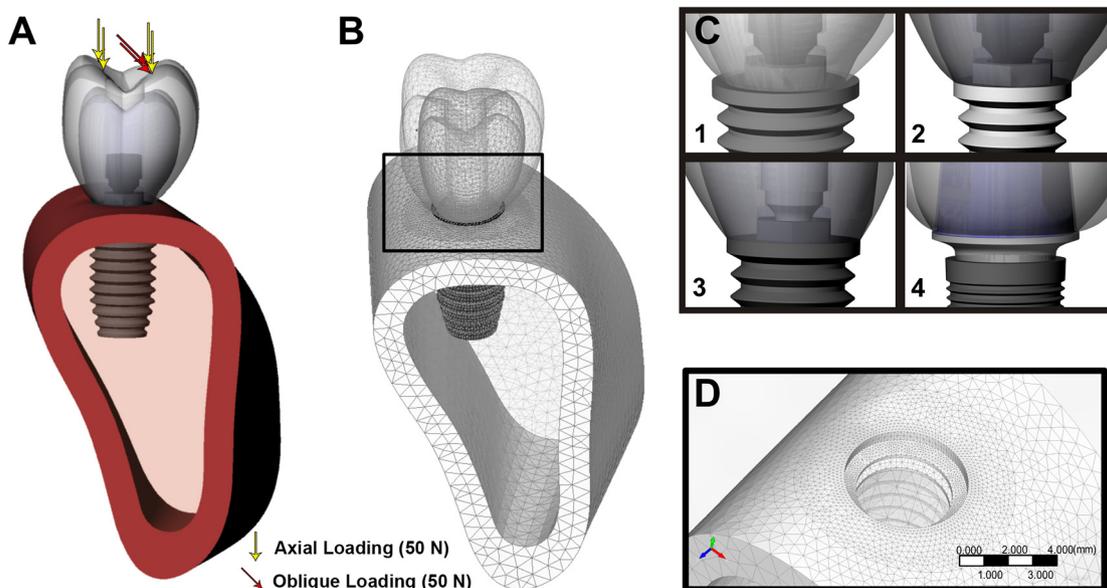
Fig. 1. A) View of the solid model PSW in bone type II; B) Mesh of finite element model C) Details of situations of implant-abutment interfaces: C1: PSW, C2: External hexagon with regular diameter, C3: External hexagon with regular platform and C4: Morse taper with regular diameter. D) Detail of the analyzed area.

Table 2
Mechanical properties.

Materials	Modulus of elasticity (GPa)	Poisson's ratio (v)	References
Trabecular bone (Bone type I, II and III)	1.37	0.3	Sevimay et al. [11]
Trabecular bone (Bone type IV)	1.10	0.3	Sevimay et al. [11]
Cortical bone	13.7	0.3	Sevimay et al. [11]
Titanium	110.0	0.35	Sevimay et al. [11]
NiCr alloy	206.0	0.33	Anusavice et al. [12]
Feldspathic porcelain	82.8	0.35	Sevimay et al. [11]

implants demonstrated better stress distribution than other models, regardless of bone type ($P < 0.001$) (Figs. 3 and 4).

3.3. Bone type analysis

Under axial loading, the bone type I showed lower stress compared to other bones types ($P < 0.05$) (Figs. 2 and 5). Bone type IV was found to be significantly different from bone types I and II ($P < 0.001$); however, no significant differences in terms of stress were observed between bone types III and IV ($P = 0.329$). Likewise, under oblique loading bone type IV proved significantly different from bone types I and II in terms of stress concentration ($P < 0.001$), yet no differences in stress were reported for bone types III and IV ($P = 0.995$), or for bone types I and II ($P = 0.140$) (Figs. 3 and 5).

3.4. Loading and region analysis

Oblique loading showed higher tensile stress (6.576 MPa) in the cortical bone when compared with axial loading (0.943 MPa) ($P < 0.001$) (Figs. 2 and 3). Region analysis revealed higher tensile stress in the buccal region (5.269 MPa) than in the lingual (2.141 MPa), mesial (3.714 MPa), or distal (3.914 MPa) ($P < 0.001$), whereas no significant differences between mesial and distal regions in terms of

tensile stress ($P = 0.338$) were observed.

4. Discussion

The first hypothesis was rejected, since significant differences were observed in the stress distribution between wide-diameter and regular-diameter implants, regardless of load conditions. These results corroborate other biomechanical studies, which have reported more favorable stress distribution in cortical bone surrounding wide-diameter implants [5,14]. This may contribute clinically to a reduced rate of marginal bone loss around wide-diameter implants [15], and an indication for their use in low quality bone tissues such as that of the posterior maxillary region [15]. Even so, the risk of bone resorption and resultant tooth loss limits the placement of wide-diameter implants, especially in this region [16].

In this study, significant differences in stress distribution were observed between implant-abutment interfaces types, rejecting the second hypothesis. PSW implants showed favorable stress distribution when compared with regular-diameter implants; however, PSW implants showed similar stress distribution around the cortical bone tissue when compared with implants of the same diameter but with a regular platform. Thus, biomechanical effects can be attributed to the diameter and not the type of abutment-implant interface. These results are consistent with findings of other studies of PSW and EH interfaces, which have indicated that the biomechanical advantage to be related to the increased implant diameter, rather than centralization of stresses as an effect of reduced prosthetic platform [17]. Nevertheless, a recent systematic review reported that PSW implants have shown clinically lower marginal bone loss values when compared with implants with a regular platform [18]; this is probably related to biological rather than specific biomechanical factors.

Some studies have shown MT implants to be biomechanically and biologically superiority [3,19], so, this study sought to determine whether regular-diameter MT implants and wide-diameter EH implants would present similar biomechanical behavior. Under axial loading, regular-diameter MT implants performed similarly to wide-diameter EH implants; however, under oblique loading conditions, wide-diameter EH implants showed better stress distribution than MT implants. Therefore, use of wide-diameter implants, independent of connection type, is recommended where it is possible to favors stress distribution and subsequent restorative treatment longevity.
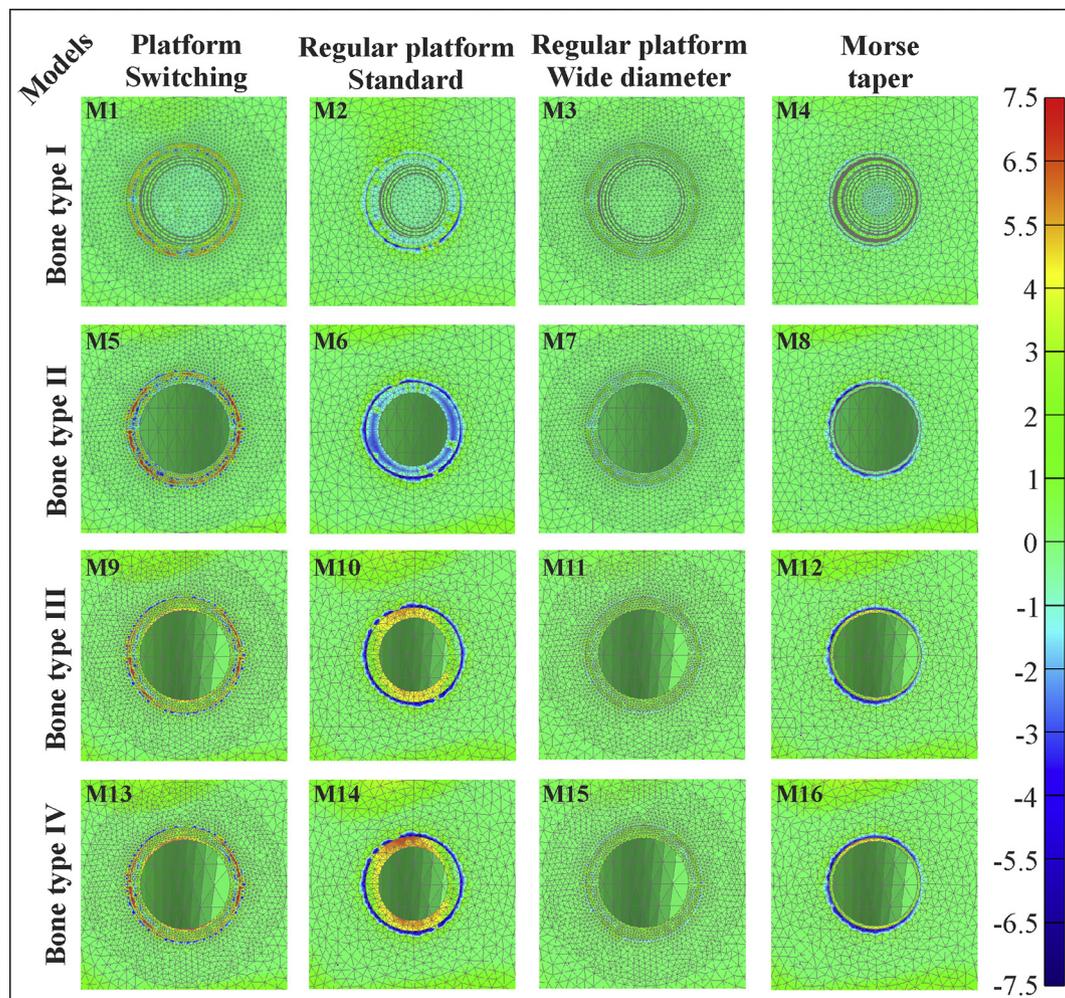
Fig. 2. Stress distribution in the cortical bone tissue by maximum principal stress (MPa) under axial loading.

Where circumstances preclude the placement of a wide-diameter implants, MT implants are recommended because they lead to lower stress in surrounding cortical bone tissue than do EH implants of the same diameter. This advantage relates to the location of the implant-abutment interface. In, MT an internal connection centralizes stress within the long axis of the implant, thereby reducing the stress in the cortical area, whereas the EH implant connection is presented externally near cortical tissue, thereby contributing to increased stress and potential bone loss in the region [1,3]. These results may also could be related to the different prosthesis fixation methods used [20]. MT implants for rehabilitation of single-unit crown are recommended with cement-retained prosthesis [21], mainly with a solid abutment (one-piece) without screw fixation. These factors could contribute the favorable results for MT implants compared to EH implants from the same diameter.

Clinical evidence supports the findings of this biomechanical study, with lower rates of marginal bone loss surrounding MT than EH implants [22,23]. Moreover, the presence of a stable internal connection can reduce micromotion in the cortical bone region and provide a bacterial seal, leading to lower clinical values for marginal bone loss with MT implants [24].

The third hypothesis was rejected, since bone tissues types did demonstrate an influence on stress distribution. These results support a direct correlation between bone tissue density and stress concentration, especially under oblique loading [11]. Bone type IV, found in the posterior maxillary region, is lower in bone density than other bone types, and is associated with lower implant survival rates [8]. Cortical

bone thickness is another factor that may influence stress responses in bone tissue [25]. According to Lekholm and Zarb [10], bone types III and IV showed relatively low cortical bone thickness (1 mm), which may contribute to higher stress in the region [3]. The above-mentioned findings were corroborated by the results of this study, which showed that despite the similarity of bone type III to types I and II in terms of density, it was between bone types III and IV that no significant differences were found, possibly due to a similar thickness of cortical bone [3,11]. Cortical bone thickness is also considered an important factor in rehabilitation planning. With an elasticity modulus approximately 10 times greater than that of trabecular bone tissue [11], cortical bone appears to protect this adjacent tissue, and consequently a loss or reduction of cortical bone is likely to compromise rehabilitation outcome [26].

Thus, reverse planning for implant placement should be accurate to avoid possible bone tissue overload and rehabilitation compromise. It is noteworthy that the conditions tested on cortical bone in this study did not exceed physiological limits for tensile and compressive stresses (72 to 76 MPa and 140 to 170 MPa, respectively) [27]. Although the finite-element method is considered a favorable tool for analysis of stress distribution, but it has certain limitations that may affect results. For example, materials properties of bone are assumed to be isotropic, homogeneous, and linear, unlike bone tissue in vivo, which exhibits anisotropic and non-homogeneous characteristics. Therefore, further randomized controlled trials should be conducted to gain a better understanding of the influence of these variables.
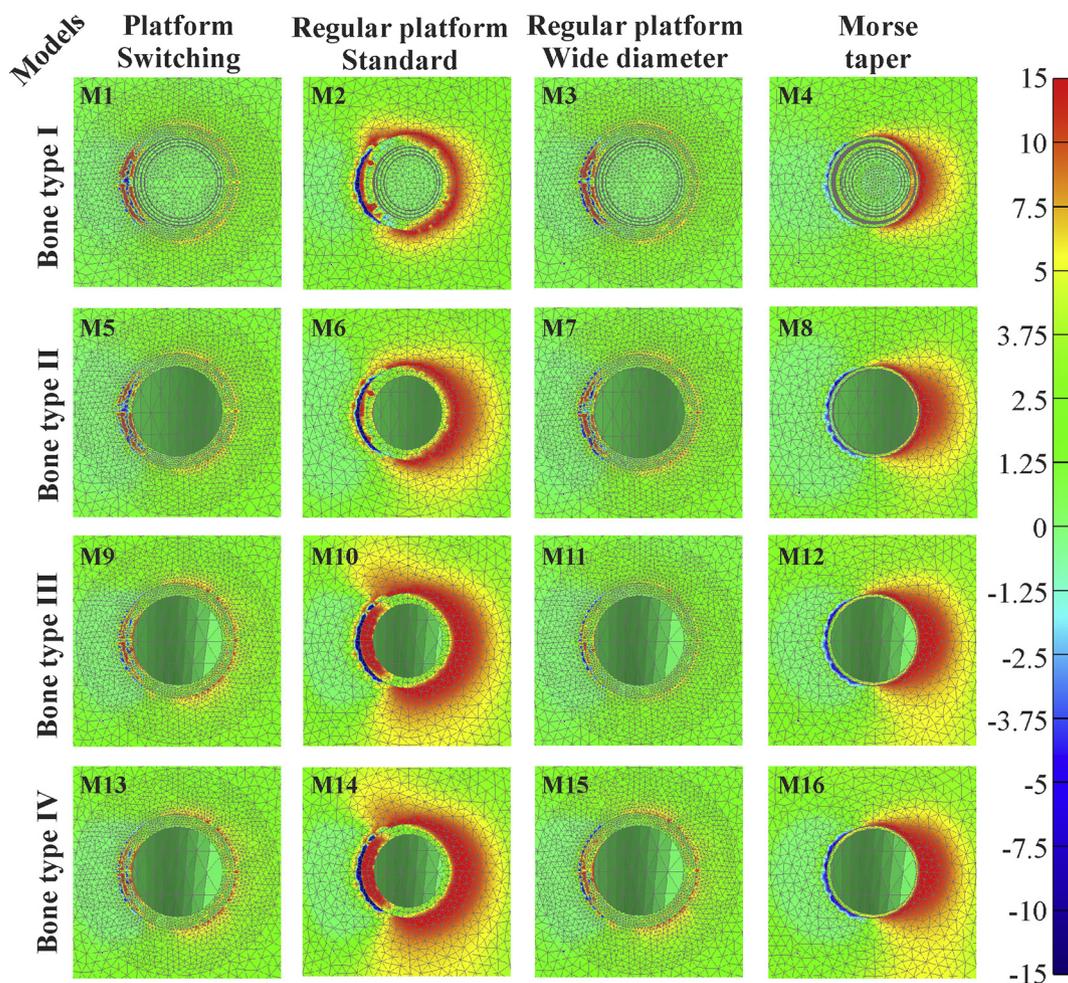
Fig. 3. Stress distribution in the cortical bone tissue by maximum principal stress (MPa) under oblique loading.
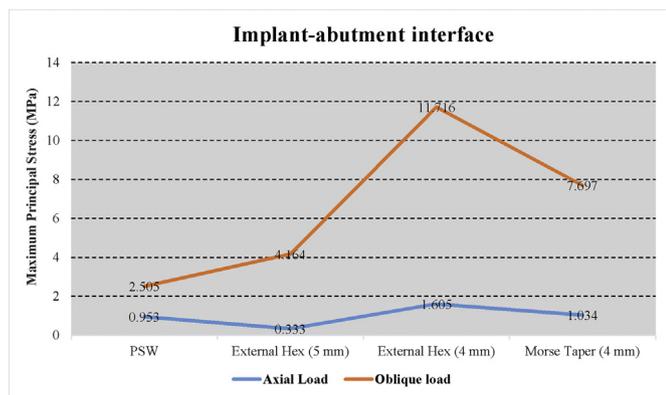
Fig. 4. Peak maximum of stress implant-abutment interfaces under axial and oblique loading.
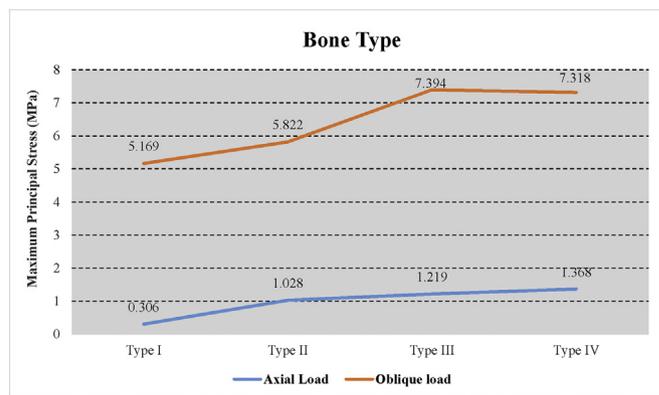
Fig. 5. Peak maximum of stress in the bone types under axial and oblique loading.

5. Conclusion

Within the limitations of this in silico study, it can be concluded that wide-diameter implants show more favorable stress distribution than regular-diameter implants; MT implants show more favorable stress distribution than regular-diameter EH implants; and bone types III and IV show higher stress in the cortical region than bone types I and II. Thus, wide-diameter implants are recommended for first preference use, and where this is not possible, MT implants should be considered, particularly for bone types III and IV.

Acknowledgements

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