Stress Evaluation of Implant-Abutment Connections Under Different Loading Conditions: A 3D Finite Element Study

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This study evaluated the effects of axial and oblique occlusal loading on implant-supported partial dentures with different connection systems (external hexagon, internal hexagon, and Morse taper). Upon axial loading, all systems presented similar stress values. Stress values increased under oblique loading. Stress distribution changed for some of the internal connection structures. It can be concluded that oblique load increases stress on bone structures and prosthetic components. Internal connection system implants present more favorable stress distribution patterns than do external connection system implants.

Key Words: finite element analysis, dental implants, occlusal loading, connection system

INTRODUCTION

Biomechanical factors must be seriously considered during the planning of implant-supported restoration because of their key role in bone resorption and the fracture of prosthetic components and frameworks.[1] Occlusal load transfer at the bone-implant interface depends not only on the occlusal load but also on the material from which the prosthesis is manufactured, the nature of the bone-implant interface, bone quantity and quality, and the geometry of the implant selected for restoration (length, diameter, and shape).[2,3]

Research has shown that when it comes to implant design, the implant thread profile[4,5] and the implant shape[6] influence the stress distribution of occlusal load over the supporting bone tissue. The implant-abutment connection system has also been reported as potentially affecting stress distribution on bone and prosthetic components.[7–9]

Several abutment connection systems exist, each presenting advantages and disadvantages for patient restoration. The conventional external hexagon connection (butt joint) has been reported as advantageous for its anti-rotational mechanism, ease of prosthesis removal, and compatibility among different implant systems. Nonetheless, external hex connections might be considered slightly unstable due to the height of the hexagon, allowing for prosthesis micromovement and rotation. Internal hexagon connection systems are advantageous for producing anti-rotational, stable, and more resistant restoration with better force distribution. However, in internal hex restorations, adjustment of divergent implant angles might be difficult. Among the internal connection types, the taper joint system with a conical seal, or Morse taper, presents some of the advantages of the internal hex connection coupled with a better sealing of the joints.[8] Taper joint connections are considered to be more stable and resistant than other connections, but they are also more difficult to release when necessary.

Due to the wide variations in available implant and prosthetic systems, implant-supported restoration must be carefully planned for optimal biomechanics. It is extremely difficult to conduct clinical trials to evaluate stress distribution on implant-supported prostheses. Thus, finite element (FE) studies have been performed,[2–7,9] simulating possible clinical conditions and aiming to verify stress distribution on bone structures and prosthetic components. Few studies have been performed since masticatory load is oblique, with both axial and lateral force components.

It is known that vertical loads from masticatory movement induce both axial forces and bending moments that will affect stress in implant and bone structures.[2] Excessive occlusal loading might be responsible for bone resorption and osseointegration loss, compromising the longevity of the implant-supported restoration. The stress generated by occlusal loads is directly related to the types and distributions of these loads, associated with the mechanical properties and design of the implant assembly and the prosthetic framework.[10]

Thus, the aim of this study was to evaluate the effect of occlusal load direction on the stress of implant-supported partial dentures manufactured with different implant-abutment

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connection systems (external hexagon, internal hexagon, and Morse taper).

MATERIALS AND METHODS

Three-dimensional solid-element-based finite element (FE) models were built, reproducing the clinical situation of a mandibular implant-supported restoration (SolidWorks 3D CAD Design Software, Dassault Systèmes, SolidWorks Corporation, Concord, Mass). A posterior section of the mandible was modeled with a 1.5-mm-thick cortical bone layer. A 3-element fixed partial denture framework, supported by 2 dental implants, was designed to restore first and second premolars and the first molar. Three assemblies were modeled, consisting of sets of 2 implants (4.1 mm × 11 mm), 2 conical abutments, 2 prosthetic screws, and a metal framework. All implants were placed at the bone crest level. Implant-abutment connection systems varied for each assembly: external hex connection (EH), internal hex connection (IH), and Morse taper connection (MT). All implants and prosthetic components that were modeled reproduced the same implant design, with different connections (Titamax, Neodent, Curitiba-PR, Brazil). The modeled prosthetic components were also integrated with the selected implant system. Implant and abutment were modeled as one piece for the MT models.

The meshes of the finite element models were obtained automatically with 3-dimensional parabolic tetrahedral elements used to generate compatible meshes among all parts of the model. Each model was generated with the same element size set at 0.35 mm (CosmosWorks, Dassault Systèmes). Boundary conditions for all models were set on both sides of the bone section.

Compressive load was applied over the entire occlusal surface of the prosthetic framework. For the exclusively axial loading (AX), 180N was applied to the first premolar and first molar, and 280N was applied to the second premolar.[11] For the oblique loading case studies (OB), axial and lateral force components were applied, resulting in 63° oblique loading with the same magnitude as that of the AX models (Figure 1).

All materials were considered to be isotropic, homogeneous, and linearly elastic. The materials' mechanical properties (Poisson ratio and Young modulus) were as follows:[2,4,12] implants and prosthetic framework, commercially pure titanium (0.3; 117 GPa); abutment and prosthetic screws, Ti-6Al-4V (0.31; 110 GPa); cortical bone (0.3; 13.7 GPa); and trabecular bone (0.3; 1.37 GPa). Maximum von Mises stress values were determined, as were the stress distribution patterns for each model. Colored diagrams were obtained with FEMAP version 8.3 (Siemens PLM Software, Plano, Texas) and are presented for the visualization of the models' stress distribution characteristics. The models are labeled according to the implant-abutment connection system (EH, IH, or MT) and the loading condition (AX or OB).

RESULTS

All FE models presented similar numbers of nodes and elements. The EH model presented 1 490 816 nodes and 1 073 719 elements; the IH model presented 1 492 945 nodes and 1 073 671 elements; and the MT model presented 1 472 904 nodes and 1 062 819 elements. The data obtained from the FE analyses are presented as the associated von Mises stress, providing maximum stress values for each model (Table).

Upon axial loading (AX), the IH model presented higher maximum stress value on the cortical bone structure compared with the other connections. However, on trabecular bone, IH-AX and EH-AX presented similar maximum stress values, while MT-AX presented a lower stress value. Higher stress values were observed around the implant neck on the cortical bone (Figure 2a) and at the bottom of the implants on the trabecular bone (Figure 3a). Higher stress was observed at the implant platform (Figure 4a). The implant connection did not influence the stress distribution pattern on all evaluated structures.

On the abutments, maximum stress was located at the abutment platform, at the interface between the framework and the abutment (Figure 5a). Prosthetic frameworks presented similar maximum stresses for all models. Higher stress intensity was located at the bottom of the framework, at the contact surface with the abutment (Figure 6a). Despite the differences in maximum stress values on the prosthetic screws, stress location was similar for all models at the screw neck (Figure 7a).

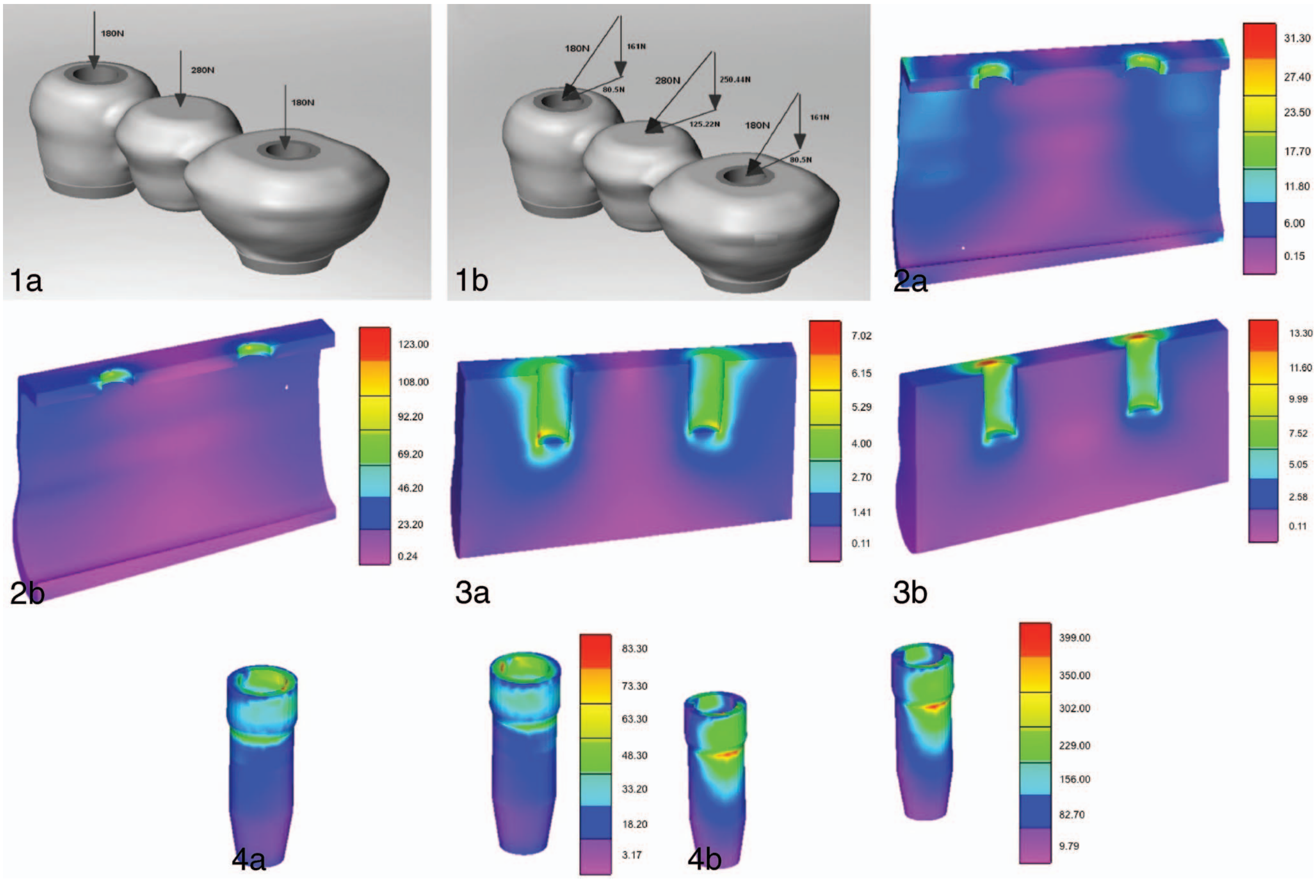
Oblique loading increased the maximum stress values of all evaluated structures (Table) and changed the stress concentration area on all structures. No difference in stress distribution patterns was observed among models with different implant connection systems. Distribution patterns of maximum stress on cortical bone were similar to those of the axial loading condition (Figure 2b). For trabecular bone, high stress values were observed on the surface, close to the implant neck, and at the bottom of the implant (Figure 3b). On the implants, maximum stress values were located at the neck (Figure 4b). The EH implant presented higher maximum stress value.

On the abutments, higher stress areas were observed at the contact interface between the abutment and the implant (Figure 5b). Maximum stress values and stress distributions on the frameworks remained similar for all models, with higher stress concentration at the bottom of the framework (Figure 6b). The same was observed for prosthetic screws (Figure 7b).

DISCUSSION

Stress distribution patterns of implant-supported restorations have often been evaluated by strain gauge, photoelasticity, and finite element methods. It has been suggested that some features of implant-supported restorations might affect the stress magnitude and distribution patterns on supporting bone.[4–6] Implant connection systems have also been reported as potentially affecting stress distribution on bone and prosthetic components.[7–9] Nevertheless, there is no agreement on the actual effect of this parameter on stress of implant-supported restorations.[7,13]

In the present study, 3 commonly used implant connection systems were evaluated using FE modeling. Finite element models were obtained simulating 3-element implant-supported fixed partial restorations, using implants with external hexagon, internal hexagon, and Morse taper connections. The models were subjected to 2 loading conditions, with exclusively axial loading or with the combination of both axial and lateral forces,



Figures 1–4. Figure 1. Occlusal loading schemes. Single arrows illustrate only loading direction: (a) Axial loading. (b) Oblique loading. **Figure 2.** Cortical bone, von Mises stress (MPa). Maximum stress surrounding the implant. (a) Axial loading. (b) Oblique loading. **Figure 3.** Trabecular bone, von Mises stress (MPa). On AX models, maximum stress is located at the bottom of each implant, while on the OB models, maximum stress is located also at the surface of the trabecular bone. (a) Axial loading. (b) Oblique loading. **Figure 4.** Implants, von Mises stress (MPa). Maximum stress location changed from the implants' platform (AX models) to the implants' neck (OB model). (a) Axial loading. (b) Oblique loading.

simulating occlusal loading. Loading forces were obtained based on results from a previous report[11] and were applied over the entire occlusal surface of each tooth modeled in the framework, for equal distribution of stress to the other modeled structures.[3,14]

In the present study, the evaluated connection systems presented slight changes in maximum von Mises stress values. Nonetheless, stress distribution patterns were similar for all models upon axial loading. These results corroborate those of previous studies[7,15] in which, upon axial loading, similar stress distribution patterns and stress values were obtained for EH, IH, and MT systems.

Occluding masticatory forces induce both axial and lateral forces, initiating bending moments that will affect stress in the implant and bone structures.[2,16] It is known that vertical components of occlusal forces are much higher than those of oblique and horizontal forces;[6] thus, a 2:1 ratio was determined for the axial and lateral forces simulated in the present study.

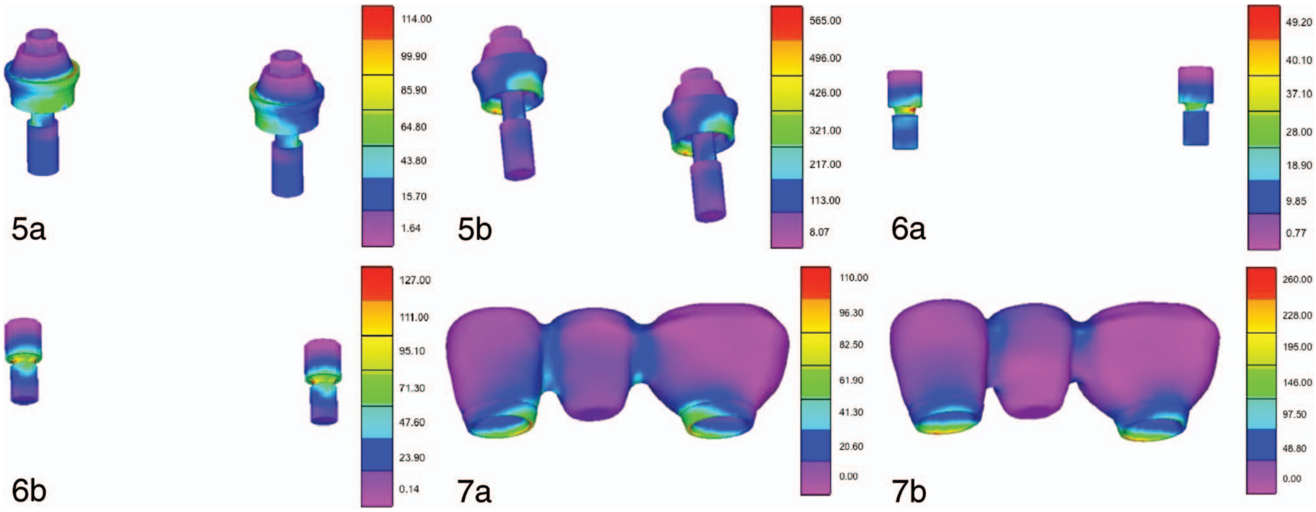
Table

Maximum stress values (MPa) presented by the models evaluated*

Model		Cortical Bone	Trabecular Bone	Implants	Abutments	Prosthetic Screw	Framework
EH	AX	31.30	7.02	90	114	49.20	110
	OB	123	13.30	605	565	127	260
IH	AX	35.30	7.10	83.30	105	71.90	102
	OB	139	12.90	399	416	66.20	264
MT	AX	33.20	5.58	132†		67.60	112
	OB	125	9.32	882†		210	279

*EH indicates external hex connection; AX, axial loading; OB, oblique loading; IH, internal hex connection; MT, Morse taper connection.

†On the MT model, implant and abutment were modeled as one piece; therefore, maximum stress values were obtained for this combined piece.



Figures 5–7. Figure 5. Abutments, von Mises stress (MPa). Maximum stress concentration changed from the contact area between the abutments and the framework to the contact area between the abutments and the implants. (a) Axial loading. (b) Oblique loading. **Figure 6.** Frameworks, von Mises stress (MPa). Stress distribution was similar for both loading conditions, with increased maximum stress value upon oblique loading. (a) Axial loading. (b) Oblique loading. **Figure 7.** Prosthetic screws, von Mises stress (MPa). Maximum stress around the screws' neck. (a) Axial loading. (b) Oblique loading.

From the combination of the force components determined for both loading axes, a resulting force at a 63° angle to the horizontal plane was obtained and applied to the occlusal surfaces of the frameworks.

Maximum von Mises stress increased at all the evaluated structures upon oblique loading.[17,18] Stress at cortical bone was approximately fourfold the stress with axial loading. Trabecular bone and prosthetic frameworks presented nearly twice as much stress under oblique loading. Implants, abutments, and prosthetic screws presented even higher increased stress values. The increased stress upon oblique loading was expected since the presence of lateral forces during occlusion generates a bending moment within the prosthesis, prosthetic components, and the supporting implants that influence principal stresses and von Mises stress values of the restoration structures.[19]

In addition to increasing the maximum stress values of the structures, oblique loading promotes change in some of the stress concentration areas. Trabecular bone presented stress concentration areas at both the apex of the implant and close to the implant platform. Upon oblique loading, the stress distribution area may be greater, mainly in the direction opposite of where the load is applied.[20] Higher stress was also concentrated in a lower portion of the implant cylinders and the abutments when compared with the location on axially loaded models, which probably occurred as a result of the bending moment initiated by the oblique loading of the restoration.[2,16]

The different connection systems that were evaluated presented minor differences in stress intensity. However, internal connection systems presented a tendency toward lower stress values. Upon oblique loading, the MT connection presented lower stress at trabecular bone, while the IH connection presented lower stress at implants, abutments, and prosthetic screws. These findings are in agreement with those of other studies, in which internal connection systems presented lower stress concentrations than did external connection systems.[15,19,21] The internal connection systems' lower stress values might be a consequence of the greater contact area between the abutments and the implants. Increased contact area between these structures may reduce the effect of bending caused by the horizontal component of the oblique load.[7] In addition, internal connection systems present greater stability than do EH systems,[22] which may contribute to stress values and distribution. When both internal connection systems were compared, it was observed that the IH model presented higher stress on trabecular bone and lower stress on prosthetic structures, while the MT model presented higher stress on the prosthesis structures and lower stress on cortical and trabecular bone.[9] Nonetheless, both internal connection models presented lower stress on either trabecular bone or prosthetic components.

Excessive load on implant-supported restorations is known to be responsible for bone resorption around the dental implant.[23] Cortical bone structure is known to present higher stress concentrations than trabecular bone; hence, the resorption pattern was frequently observed. Ultimate tensile and compressive strengths of cortical bone have been reported at around 100–121 MPa and 167–173 MPa, respectively.[24,25] Although some information is available regarding ultimate compressive and tensile strength and strain resistance, the in vivo stress values that actually cause biological changes, such as resorption and remodeling in the bone, are not presently known.[26] Therefore, reduced stress values and more equal stress distribution should be the primary goal of implant-supported restoration.

Within the limitations of this study and considering the assumptions made for these FE models, it can be concluded that stress on the restoration is much higher upon oblique loading; thus, stress analyses simulating oblique loading should be performed. Further, the slight differences between stress values suggest that internal connection systems present a more favorable stress pattern than do EH connection systems.

Abbreviations

AX: axial loading
EH: external hex connection
FE: finite element
IH: internal hex connection
MT: Morse taper connection
OB: oblique loading

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