Finite Element Analysis of Biomechanical Interactions of A Tooth-Implant Splinting System for Various Bone Qualities

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Background: The splinting of an implant and tooth is a rational alternative in some clinical situations. The complex biomechanical aspects of a tooth-implant system are derived from the dissimilar mobility between the osseointegrated implant and the tooth. The aim of this study was to analyze the biomechanics in a tooth-implant splinting system for various bone qualities with different occlusal forces using non-linear finite element (FE) analysis.

Methods: A 3D FE model containing one Frialit-2 implant splinted to the mandibular second premolar and a simplified bony segment was constructed. Four bone quality categories were established by varying the elastic parameters assigned to the bone volumes. Contact elements (frictional surface) were used to simulate the realistic frictional interface condition within the implant system. The stress distributions in the splinting system were observed for four loading types.

Results: The simulated results indicated that the lateral occlusal forces significantly increased the implant system ($\sigma_{I,\ max}$), alveolar bone ($\sigma_{AB,\ max}$) and prosthesis ($\sigma_{P,\ max}$) stress values when compared with the axial occlusal forces. The $\sigma_{I,\ max}$ and $\sigma_{P,\ max}$ values did not exhibit significant differences between the four bone qualities. Conversely, the $\sigma_{AB,\ max}$ values increased with reduction in bone quality, in particular for type IV bone quality. The $\sigma_{I,\ max}$, $\sigma_{AB,\ max}$ and $\sigma_{P,\ max}$ stress values were significantly reduced in centric or lateral contact situations once the occlusal forces on the pontic were decreased.

Conclusions: This study suggests that implants connected to natural teeth should be used with caution in softer bone regions. Utilizing occlusal adjustment to minimize the occlusal loading force on the pontic could reduce the stress/strain values in the splinting system.

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Key words: tooth-implant splinting, bone quality, finite element analysis, biomechanics.

Although dental implants have been used extensively for the rehabilitation of complete and partial edentulous jaws with either fixed or removable prostheses,[1-5] whether implants should be connected to natural teeth remains a contentious issue.[1,3,6,7] When splinting the implant and tooth is considered a rational alternative, a biomechanical dilemma in a tooth-implant supported system results

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from the dissimilar mobility between an osseointegrated implant and the tooth. A series of engineering and physiological problems associated with the implant connection to a natural tooth involve abutment screw loosening, prosthesis fracture and intrusion by the natural tooth resulting from the higher bending moment caused by the cantilever effect when the system is loaded by occlusal forces.[1,3,6] To stabilize the dissimilar mobilities between natural teeth and implant systems, non-rigid connectors (keyway attachments) with the ability to separate the splinted units have been devised to compensate for the mobility discrepancy. This method has been suggested and commonly used with conventional fixed partial dentures (FPDs) in past decades.[3,8-10] However, clinical observations have doubted their function and most of them have revealed non-significant or minimal differences between rigid and non-rigid tooth-implant connections.[10-12] Therefore, certain authors have advocated rigid implant to tooth connections when mechanical binding and tooth intrusion are considered in the splinting system for long-term use.[6,13-16]

Despite the biomechanical aspects being important factors influencing the long-term success of a tooth-implant supported system,[7,17-19] the fundamental mechanics are still unclear, especially when various bone qualities are considered in the splinting system. Bone quality has been accepted as one of the key issues influencing the long-term success of implants. The classification for bone quality proposed by Lekholm and Zarb (1985) has been widely applied by clinicians when evaluating a patient's bone for implant placement.[20-23] Several studies correlating single implant success have suggested that poor bone quality exhibited the greatest failure rates owing to thin cortex bone and low-density trabecular bone with low capability to react properly to the stresses/strains generated by occlusal loads.[24] Increased bone density was demonstrated to have less micro-movement and increased initial stability in single implant fixtures.[25,26] When implant to tooth splinting is planned, dissimilar micro-movements between the implant and tooth are recognized as the initial major factor inducing a splinting system to fail. Unfortunately, insufficient research has focused on the effects of mechanical interactions for tooth-implant supported systems under various bone quality situations. Hence, we deem it necessary to investigate the influences of bone quality on the micro-movements in both an implant and natural tooth to understand the basic mechanisms of a splinting system.

To date, reported experimental approaches/clinical observations do not provide enough information to determine the biomechanics of complicated tooth-implant supported systems. The finite element (FE) method provides detailed mechanical responses and alters parameters in a more controllable manner, influencing its common use as an analytical tool in dental biomechanical studies.[7,16,27] Nevertheless, it is an undisputed fact that the analytical results have often been ambiguous because of unrealistic assumptions.[16] Linear FE analysis is not the actual scenario for most available dental implants, such as the specific implant-abutment/implant-screw interface parts separating under loads. Therefore, non-linear FE analysis with reasonable interface conditions (frictional surface) that can simulate the inherent flexibility within the implant system is necessary in advanced computer simulations. Accordingly, the aim of this study was to investigate the mechanical interactions in a rigid implant-tooth splinting system under various bone qualities with various occlusal forces using nonlinear FE analysis.

METHODS

FE model of tooth-implant supported system

A simplified mandibular segment, assumed edentulous distal to the second premolar with a cancellous core surrounded by two 0.75 mm thick cortical layers was modeled as the partially dentate model. A freshly extracted intact second premolar was embedded 1 mm below the cementum-enamel junction (CEJ) into an epoxy resin block, 24 mm in height, 30 mm in mesiodistal length and 12 mm in buccolingual width, treated as the bony block. Three-unit prosthesis fabricated with type II gold alloy was fixed adhesively on to the natural tooth. The upper region (prosthesis) of the system was then embedded again to expose the tooth-resin-prosthesis sections parallel to the mesial-distal direction using a low speed diamond saw (Isomet, Buehler, Illinois, USA). The dentine, pulp and prosthesis boundaries from each sectioned digital image were detected using an in-house developed image processing program.[28] The coordinates of each point on the boundaries were entered into the FE package (ANSYS) to build solid models of the tooth and prosthesis. A simplified 0.25 mm thick periodontal ligament layer (PDL) was modeled based on the root-form geometry of the premolar. One Frialit-2 root-form implant, 4.5 mm in diameter and 13 mm in length, with a screw-retained MH-6 abutment (Friadent GmbH, Mannheim, Germany) was used as the investigated implant system and designed at the second molar position to complete the splinting system solid model (Fig. 1).

The mesh model was generated using a mapping approach with eight-node iso-parametric brick elements (solid 45), and nonlinear frictional contact elements (contact 49, defined as node to surface) with friction were used to simulate the adaptation between the various components within the implant system (abutment/fixture, abutment screw/abutment and abutment screw/fixture). The frictional contact condition allowed the nodes to slip in the tangential direction with no penetration between the different materials. This configuration transferred the compressive and tangential forces with no tension in the contact zone. A friction coefficient value of 0.5 was assumed for all contact surfaces.(16) Using the contact mode to mimic the frictional condition between different components within the implant system has been proven as the more realistic interface fixation to more realistically simulate the relative micromotions occurring between the various components.(16) The FE model consisted of 34,792 bricks, 3,924 contact elements and 38,725 nodes (Fig. 2). The mesial and distal exterior nodes of the bony segment were fixed in all directions as the boundary conditions. Linear elastic, homogeneous, isotropic material properties of dental tissue, PDL, prosthesis and the implant system were assumed in simulations and adopted from the literature (Table 1).

Bone qualities and occlusal forces

Under frictional conditions between various components within the implant system, various qualities with four loading types were considered as the calculated modes to understand the stress/strain distributions in the implant system, alveolar bone and prosthesis.

The simulated bone quality was categorized into four types proposed by Lekholm and Zarb in 1985 and accepted by clinicians when evaluating patients for implant placements.(23) The four bone qualities were classified as follows: 1. Entirely homogeneous compact bone (BD1), 2. Thick layer (1.5 mm) of compact bone surrounding a core of dense trabecular bone (BD2), 3. Thin layer (0.75 mm) of compact bone surrounding a core of dense trabecular bone (BD3), 4. Thin layer (0.75 mm) of compact bone surrounding a core of low density trabecular bone

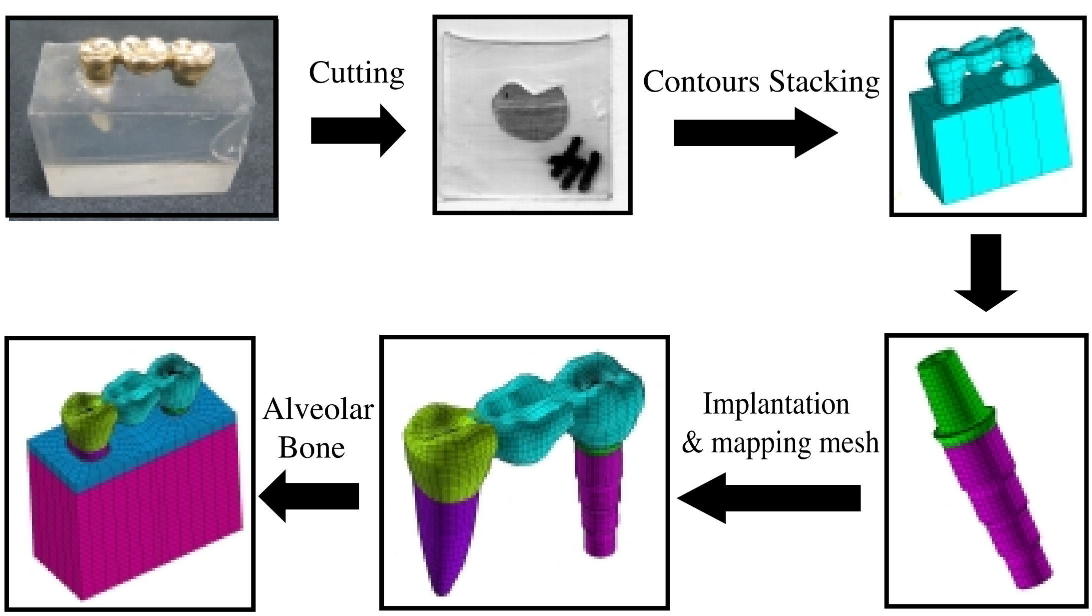


Fig. 1 Flowchart of finite element model construction.

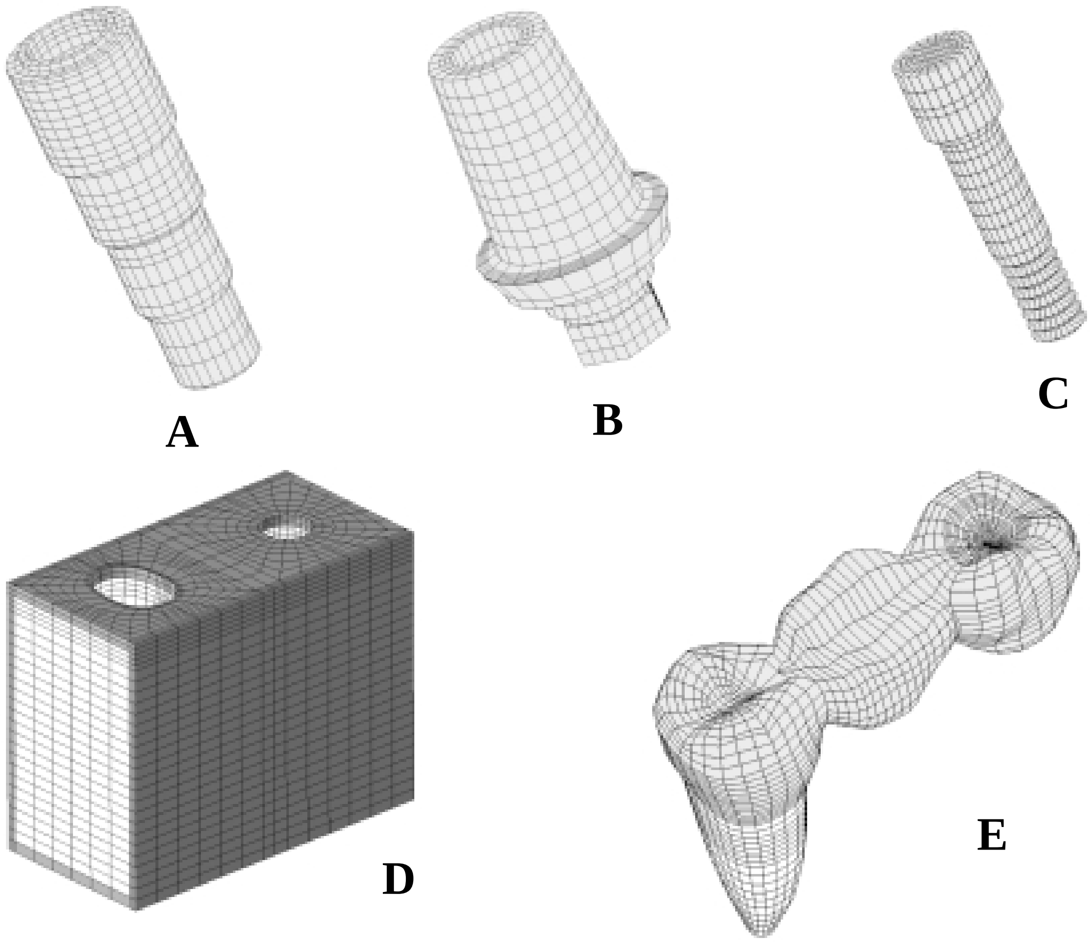


Fig. 2 A 3D finite element model of a tooth-implant supported system constructed for analysis. (A) implant (B) abutment (C) abutment screw (D) alveolar bone with 0.75 mm thick cortical layers (included periodontal ligament) (E) prosthesis and natural tooth (premolar).

Table 1. Material Properties Assigned to Implant Material, Dental Tissues, Prosthesis, Cortical and Trabecular Bone

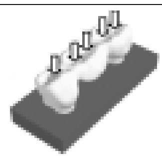
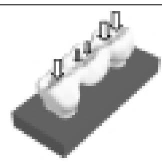
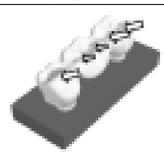
Materials	Young's modulus (MPa)	Possion's ratio	References
Titanium (Implant system)	110000	0.35	34, 35
Dentin	18600	0.31	37
Periodontal Ligament (PDL)	170	0.45	25
Gold Alloy (Prosthesis)	90000	0.3	34, 36
Cortical Bone	14800	0.3	26
Dense Trabecular Bone	1850	0.3	25
Lower Density Trabecular Bone	231	0.3	25

(BD4). All bone qualities were assumed linear elastic (homogeneous and isotropic). The Young's modulus and Possion's ratio values were adopted from the literature (Table 1). Sixteen tooth-implant supported FE models with four bone qualities and four loading conditions were simulated. Table 2 lists the detailed bone quality categorization and loading positions for these FE models.

RESULTS

The maximum von Mises stress values in the implant system ($\sigma_{I,\ max}$), alveolar bone ($\sigma_{AB,\ max}$) and prosthesis ($\sigma_{P,\ max}$) for all simulated models are shown in Figure 3. In general, lateral occlusal forces

Table 2. Detailed Loading Positions, Connecting Types and Sequence of Simulated FE Models

Loading Type		Contact Position	Bone Quality	Sequence of FE Models
1		Uniform multiple centric contacts on premolar (100N), pontic (200N) and molar (200N)	Type 1 (BD1)	1
			Type 2 (BD2)	2
			Type 3 (BD3)	3
			Type 4 (BD4)	4
2		Uniform multiple lateral contacts on premolar (100N), pontic (200N) and molar (200N)	Type 1 (BD1)	5
			Type 2 (BD2)	6
			Type 3 (BD3)	7
			Type 4 (BD4)	8
3		Uniform multiple centric contacts on premolar (100N) and molar (200N) with reduced force on pontic (40N)	Type 1 (BD1)	9
			Type 2 (BD2)	10
			Type 3 (BD3)	11
			Type 4 (BD4)	12
4		Uniform multiple lateral contacts on premolar (100N) and molar (200N) with reduced force on pontic (40N)	Type 1 (BD1)	13
			Type 2 (BD2)	14
			Type 3 (BD3	15
			Type 4 (BD4)	16

Abbreviations: FE: finite element; BD1: entirely homogeneous compact bone; BD2: thick layer (1.5 mm) of compact bone surrounding a core of dense trabecular bone; BD3: thin layer (0.75 mm) of compact bone surrounding a core of dense trabecular bone; BD4: thin layer (0.75 mm) of compact bone surrounding a core of low density trabecular bone

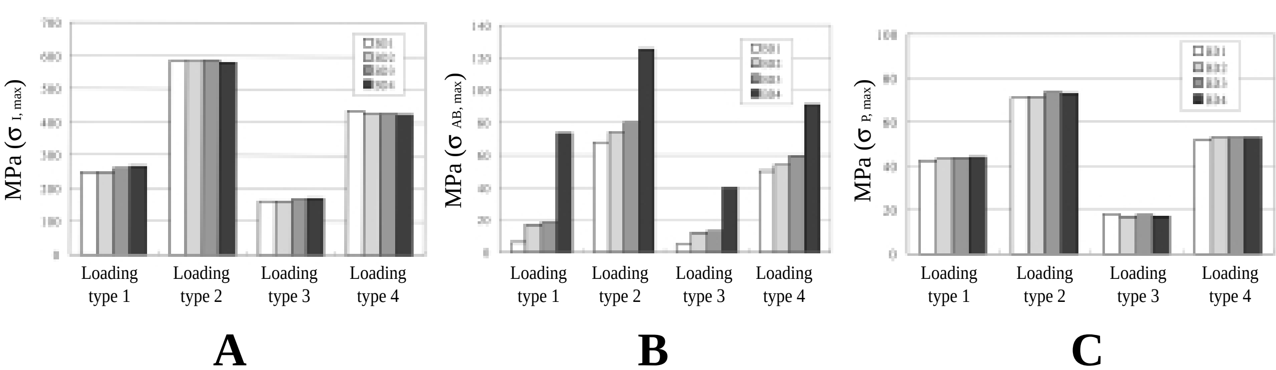


Fig. 3. Maximum von mises stress values in the (A) implant ($\sigma_{I,\ max}$); (B) alveolar bone ($\sigma_{AB,\ max}$) and (C) prosthesis ($\sigma_{P,\ max}$) with four bone qualities under axial loading (types 1 and 3) and lateral loading (types 2 and 4).

(loading types 2 and 4) significantly increased the stress values when compared with axial occlusal forces (loading types 1 and 3), regardless of the bone quality. The $\sigma_{I,\ max}$ and $\sigma_{P,\ max}$ values exhibited no significant differences between the bone qualities under the same loading condition (Figs. 3A and 3B). Conversely, the maximum stress values for the alveolar bone ($\sigma_{AB,\ max}$) increased with reduced bone quality, in particular for type IV bone quality, due to the thin cortical layer inducing high stress concentrations (Fig. 3B). When the occlusal forces acting on the pontic were adjusted to be less than that for other areas (proportion 1:5, loading types 3 and 4), the values for $\sigma_{I,\ max}$, $\sigma_{AB,\ max}$ and $\sigma_{P,\ max}$ decreased significantly. The average maximum stress variation between loading types 3 and 1 for the implant system was 35%, for alveolar bone 32% and for the prosthesis 59%. The corresponding average variations between loading types 4 and 2 were 27%, 26% and 30%.

The stress concentration locations for the 16 simulation models are also denoted. The results showed that the stress concentration regions for the implant system, alveolar bone and prosthesis were similar under axial (types 1 and 3) and lateral (types 2 and 4) loading conditions, regardless of the bone quality (Figs. 4 and 5). Type IV bone quality models under loading type 1 and 2 were chosen on behalf of all stress distribution patterns. For axial loading (1) the maximum stress concentrated locations of $\sigma_{I,\ max}$, $\sigma_{AB\ max}$ and $\sigma_{P,\ max}$ were found at the contact butt-joint of the fixture, distal cervical areas in the cortical bone and bottom of the mesial connector, respectively (Fig. 4). The corresponding locations of $\sigma_{I,\ max}$, $\sigma_{AB,\ max}$ and $\sigma_{P,\ max}$, for lateral loading (2) were at the contact butt-joint of the fixture, lingual cervical areas in the cortical bone and the lingual bonded region between the prosthesis and abutment, respectively (Fig. 5).

DISCUSSION

Although clinical investigations regard that splinting implants to natural teeth is a rational alter-

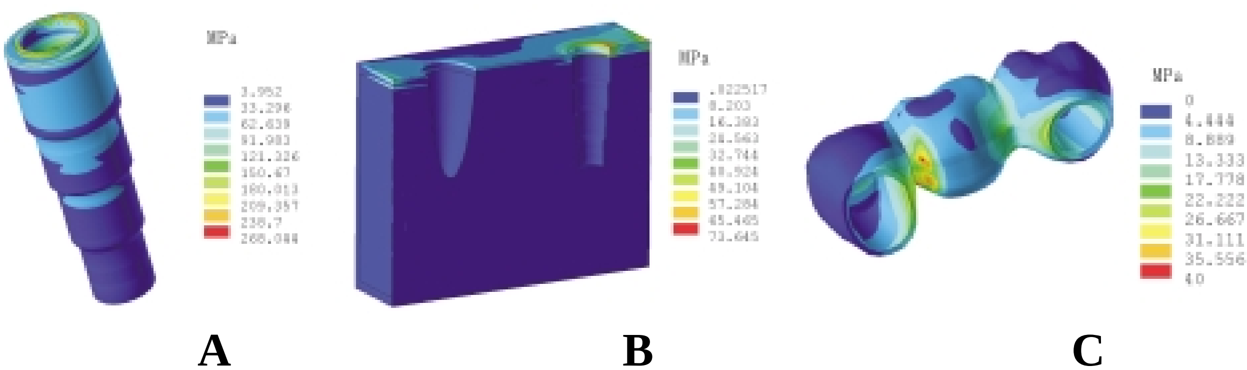


Fig. 4 Stress concentrated regions (model 4) for the implant system, alveolar bone and prosthesis under loading type 1. (A), (B) and (C) show the stress concentrated locations of $\sigma_{I,\ max}$, $\sigma_{AB\ max}$ and $\sigma_{P,\ max}$ at the contact butt-joint interface of the fixture, distal cervical areas in the cortical bone and bottom of the mesial connector, respectively.

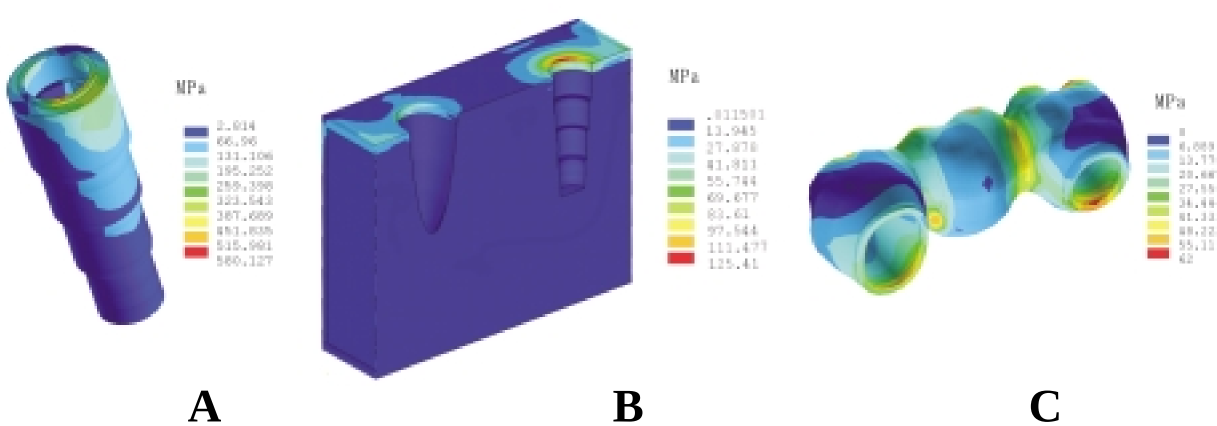


Fig. 5 Stress concentrated regions (model 8) for the implant system, alveolar bone and prosthesis under loading type 2. (A), (B) and (C) show the stress concentrated locations of $\sigma_{I,\ max}$, $\sigma_{AB,\ max}$ and $\sigma_{P,\ max}$ at the contact butt-joint of the fixture, lingual cervical areas in the cortical bone, and the lingual bonded region between the prosthesis and abutment, respectively.

native in some clinical situations,[6,10-13,15,29,30] some critical factors, such as bone quality, periodontal supports and the number of splinted teeth, significantly influence the biomechanical aspects of the splinting system. As already mentioned, bone quality is believed to be the most significant factor affecting implant survival rates. The bone's capability to withstand functional forces and react to interfacial micro-movements is critical. When splinting the implant and tooth together, different bone qualities might complicate the biomechanical aspects through dissimilar micro-movements between the natural teeth and dental implant. Therefore, bone quality seems to be one of the most important issues to consider when evaluating whether an implant should be connected to natural teeth. To overcome the limited information and sample variations in clinical or experimental approaches, FE analysis is used as the complementary tool for understanding the detailed mechanical responses of tooth-implant supported systems in this study. The accuracy of FE analysis is dependent on the numerical convergence and correctness of the assumptions imposed on the models simulating actual physical conditions, such as boundary and interfacial conditions. Consequently, non-linear contact analysis is needed to mimic a flexible implant system and provide additional information for clinical consideration.

The four loading types simulated in this study were not realistic and only simulated the possibility of axial and lateral occlusal forces found in clinical situations. In loading types 1 and 2, uniform multiple vertical and lateral forces were used to represent an implant-tooth supported prosthesis adjusted to even contact in maximum intercuspation and lateral working positions, respectively. Loading types 3 and 4 were used to compare the change in biomechanical behavior, simulating the loading magnitude on the pontic reduced in the centric and lateral contacts using selective grinding procedures. The simulation results indicated that both the occlusal contact location and force affected the stress distribution in an implant-tooth supported prosthesis with different bone qualities. The lateral occlusal forces (loading types 2 and 4) produced a lateral bending moment that significantly increased all the stress values when compared with axial occlusal forces (loading types 1 and 3), regardless of the bone quality (Fig. 4). When occlusal forces acting on the pontic were reduced to minimize the bending moment effect (loading types 3 and 4), the results indicated that the maximum stress values in the implant, alveolar bone and prosthesis decreased from 27% to 59% when compared to the values with loading types 1 and 2. This finding implies that further understanding of the role of occlusal adjustment will affect the long-term success of tooth-implant support prosthesis.

For the implant system, the maximum von Mises stresses suggested no significant differences between the bone qualities for all simulated loading types. The stress concentration regions within the implant system were found at the contact butt-joint interface between abutment and implant fixture, the bottom of the internal hexagon joint of the abutment and threads of the abutment screws. The results indicated that potential engineering problems, such as fixture-abutment interface failure, screw loosening and fracture might easily increase with long-term use. It also implies that another mechanical attachment method between abutment and fixture, such as taper integrated screwed-in (TIS) and tapered interference fit (TIF), instead of a retaining-screw, might increase the resistance to bending in implant-tooth splinting systems. In order to test this concept, a bony segment with single Frialit-2 root-form (retaining-screw) and Bicon TIF (Bicon Inc., Boston, MA, USA) implant systems were constructed and received an oblique force (100 N) to understand the variation of stress distributions within the implant system. The results showed that the stress concentrations occurred at the contact butt-joint interface for the Frialit-2 system and the tapered rod of the abutment for the Bicon system (Fig. 6). Also, the maximum von Mises stress value for the Bicon system (437 MPa) decreased significantly when compared with the Frialit-2 system (915 MPa). This result was consistent with previous experiments and supported our concept,[31] i.e. a splinting system with a TIF attachment instead of a retaining-screw might produce better results.

Splinting systems exhibited increased $\sigma_{AB,\ max}$ values with reduced bone qualities in all loading types. The stress concentration regions were found at the distal and lingual cervical areas in the cortical bone for axial and lateral loadings, respectively (Figs. 4B and 5B). When the bone quality was assumed to be type I, the stress distribution was more uniform because the entire bony block model was

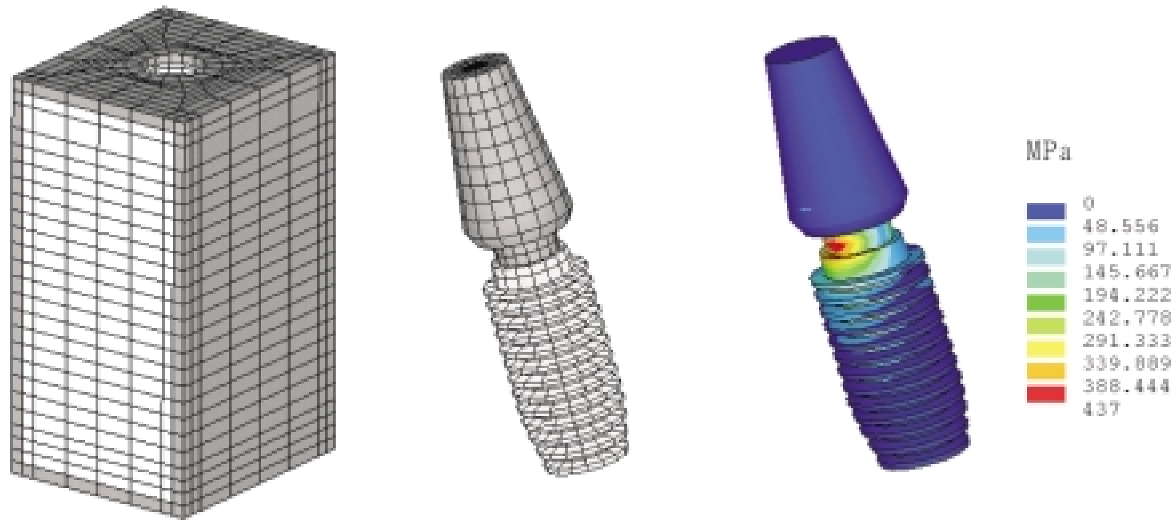


Fig. 6 (A) 3D finite element model of the bicon implant system constructed and analyzed to show variations in stress distribution. (B) Stress concentration location found at the tapered rod of the abutment.

compact bone, and the stress values were lower than those for other bone qualities (Fig. 3B). For type II and III bone qualities, the stresses were concentrated in the compact bone as cortical bone has higher elastic modulus than cancellous bone. The $\sigma_{AB,\,max}$ values for bone type III were higher than type II because the cortical shell thickness in type III was thinner than that in type II. For type IV bone quality, the stress values increased significantly due to the lowest bone density being assumed in the trabecular bone, and the maximum stress was concentrated in the thin cortical zones.

To further understand the cervical bone remodeling surrounding the implant with various bone qualities, the maximum von Mises stresses for the alveolar bone are shown in Table 3, since strain has been accepted as the mechanical stimuli to adjust bone remodeling.[32] The results show that the maximum von Mises stresses also increased with reduced bone quality. The stresses over 4000 µm/m (irreversible bone damage) were found in bone quality IV with loading types 1, 2 and 4, and bone quality III with loading type 2. The results confirm that implants connected to natural teeth should be used with caution in softer bone regions, such as the posterior maxilla. In addition, the occlusal adjustment (loading types 3 and 4) suggested that stress values could reduce efficiency when compared with uniform multiple vertical and lateral forces (loading types 1 and 2).

For the prosthesis, the stress concentrations were found at the lingual bonded region between the prosthesis and abutment for lateral loading (Fig. 5C) due to this region receiving a larger lateral bending moment. The corresponding concentrations were found at the bottom of the mesial connector for axial loads (Fig. 4C). This was caused by different mobility between the natural tooth and pontic. The bottom region of the rigid connector became a branch point

Table 3. Maximum von Mises Strains (µm/m) at the Cortical Bone Surrounding the Implant with Various Bone Qualities for Axial and Lateral Loading Conditions

Bone quality	Loading type 1	Loading type 2	Loading type 3	Loading type 4
Type 1	550	3200	320	2560
Type 2	1472	3860	810	2750
Type 3	1597	6218	1420	3218
Type 4	6419	8750	3424	4025

Type 1: entirely homogeneous compact bone; Type 2: thick layer (1.5 mm) of compact bone surrounding a core of dense trabecular bone; Type 3: thin layer (0.75 mm) of compact bone surrounding a core of dense trabecular bone; Type 4: thin layer (0.75 mm) of compact bone surrounding a core of low density trabecular bone.

for the prosthesis. These stress concentration areas might profoundly increase the failure risk after being subjected to long-term dynamic loads.

Three-dimensional non-linear contact analysis was applied in this study to investigate the basic mechanical tooth-implant supported system interactions with various bone qualities. However, based on the limitations of this numerical investigation, some of the assumptions, such as geometry of the alveolar bone and loading conditions, might determine the accuracy of the mechanical responses and stress states obtained in this study. Also, only simplified bony segments were modeled for parameter studies of the splinting system, with no attention paid to the mandibular or maxillary body effects. Although variations in bone density exist in each region, research indicated that the anterior mandible has the densest bone, followed by the posterior mandible, anterior, maxilla and posterior maxilla.[33] The simulated mandible partial dentate model with edentulous distal to the second premolar used in this study might not fully represent the variations in bone qualities existing in different regions of the mandible and maxilla. However, the results are still convincing because the simplified bony segment in our simulations was suitable for a bone density parameter study. Furthermore, as mentioned previously, loading types 1 and 2 were not realistic and assumed the possibility of occlusal forces found in clinical situations. Loading types 3 and 4 (reducing centric and lateral occlusal forces on pontic) were simulated to compare the influences of biomechanical behavior on the splinting system. Therefore, the modeling procedure limitations give only a general insight into the biomechanical aspects under average conditions, without attempting to simulate individual clinical situations. The mechanical responses obtained from all simulations are a first approximation and need to be validated with clinical trials.

Acknowledgments

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利用有限元素法探討牙齒／植體支持系統在不同骨質密度下之生物力學分析

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背 景： 植體在某些特殊的生理、解剖條件下不可避免的需和自然牙相連結，但由於自然牙和植體的動搖度並不相同使得整個牙齒／植體支持系統在受力時存在複雜的生物力學行為，本研究目的是利用非線性的電腦模擬分析針對牙齒／植體支持系統在不同骨質密度下承受不同咬合力之生物力學行為。

方 法： 研究中選定下顎第二小臼齒與遠心端無牙嵴為探討的區域，在第二大臼齒處植入一支牙根形態的植體 (Frialit-2)，然後在植體支柱和自然牙間製作一固定式補綴物，在有限元素模型建構完成、輸入材料特性及設定邊界條件之後，利用非線性的接觸性元素模擬植體各元件間有緩衝間隙存在及楔槽狀減壓裝置可相對滑動的功能，在四種不同的咬合狀態下針對系四種骨質密度進行分析以瞭解的植體、齒槽骨及補綴物之應力分佈狀態。

結 果： 分析結果顯示牙齒／植體支持系統在不同骨質密度條件下，若承受側向咬力時均會使植體、齒槽骨及補綴物之應力值大幅升高。植體及補綴物的應力值在不同骨質密度條件下承受不同咬力時變化並不大，然而齒槽骨的應力值明顯會隨骨質密度下降而大幅升高。此外，若調整橋體的咬合狀態使作用在植體端的彎曲力矩能效應減小時則可大幅降低植體、齒槽骨及補綴物之應力值。

結 論： 本研究結果顯示當牙齒與植體需連結於齒槽骨密度較低之區域需注意可能使系統的應力值大幅升高，咬合力大小和咬合接觸點兩者皆影響牙齒／植體支持系統的應力分佈，而利用咬合調整方式的確可以降低懸桁樑效應和重新分配植體系統內的應力形態。

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關鍵字： 連結，骨質密度，有限元素分析，生物力學。

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