Biomechanical Response of Implant Systems Placed in the Maxillary Posterior Region Under Various Conditions of Angulation, Bone Density, and Loading

Chun-Li Lin, MS, PhD[1]/Jen-Chyan Wang, DDS, MS[2]/Lance C. Ramp, DMD, PhD[3]/Perng-Ru Liu, DDS, MS, DMD[4]

Purpose: *The aim of this study was to determine the relative contribution of changes in implant system, position, bone type, and loading condition on the biomechanical response of a single-unit implant-supported restoration using nonlinear 3-dimensional finite element analysis (3D FEA).* ***Materials and Methods:*** *FEA models of a single-unit (crown) restoration supported by the Frialit-2 implant and MH-6 abutment or the Straumann standard implant with the Straumann solid abutment were used. Each system was analyzed by FEA with both straight and 20-degree angled abutments. Simulated implant placement was performed in the maxillary premolar area with 3 variations in implant orientation relative to the residual ridge. Analysis of each orientation was conducted for each of 4 bone quality types described by Lekholm and Zarb, with lateral and axial loading conditions imposed. The effect of each variable was expressed as a percentage of the total sum of squares as computed using analysis of variance.* ***Results:*** *Larger strain values were noted in cortical bone with lateral force and the Frialit-2 system. Bone strain increased with decreasing bone density and was affected primarily by bone quality. Implant stress was influenced mainly by implant position.* ***Conclusions:*** *Better stress/strain distribution is possible when implants are placed along the axis of loading with multiple areas of cortical contact. The Straumann solid abutment performed better as a force-transmission mechanism.* INT J ORAL MAXILLOFAC IMPLANTS 2008;23:57–64

Key words: *abutment-implant connection, biomechanics, bone type, finite element analysis, implant placement*

Oral rehabilitation with osseointegrated implants is an effective treatment for the replacement of teeth, with long-term clinical studies reporting 95% survival for mandibular implants and 65% to 85% survival for maxillary implants.[1–3] Failure may result from loss of osseointegration or component failure subsequent to restoration and may be related to unfavorable loading or to high stress concentrations.[4,5] Bone quality is also an important factor, with more failures found in bone of lower density.[6,7] Clinically, these factors are difficult to investigate because of limited information and sample variation.

Ideally, the implant should be surrounded by a layer of investing bone with a minimum thickness of 1 mm for optimal osseointegration.[8] A frequent barrier to optimal implant placement in the posterior maxilla is the presence of bony irregularities. The operator may place the implant such that loading will be directed down the long axis of the implant, with the possible risk of decreased thickness of investing bone.

Alternatively, the implant may be placed with an angulation similar to a tooth, thus increasing the likelihood of lateral loading. The influence of implant angulation on stress is a matter of debate. Some

[1]Associate Professor, Department of Mechanical Engineering, Chang Gung University, Tao-yuan, Taiwan.
[2]Associate Professor and Chair, Department of Prosthodontics, Kaohsiung Medical University Faculty of Dentistry, and Kaohsiung Medical University Hospital, Kaohsiung, Taiwan.
[3]Associate Professor, Department of Comprehensive Dentistry, University of Alabama at Birmingham, School of Dentistry, Birmingham, Alabama.
[4]Associate Professor and Chair, Department of Comprehensive Dentistry, University of Alabama at Birmingham, School of Dentistry, Birmingham, Alabama.

Correspondence to: Dr Jen-Chyan Wang, 100 Shih-Chuan 1st Road, Kaohsiung City 807, Taiwan. Fax: +886 7 3210637. E-mail: cgucaeb@yahoo.com.tw

Table 1 Simulated Implant Components Used

Implant	Diameter (mm)	Length (mm)	Abutment	Abutment connection	Manufacturer
Frialit-2 (FRI)	4.5	13	MH-6, straight and 20-degree angled	Internally hexed, separate abutment screw	Friadent, Mannheim, Germany
Straumann (STR)	4.1	12	Solid abutment, straight and 20-degree angled	One-piece Morse taper with threaded apical terminus	Straumann, Basel, Switzerland

research has demonstrated that stress in the angled implant would increase 5-fold under lateral loading.[9,10] However, other investigations have shown that the stress level incurred with the use of angled abutments, although elevated, remains within the physiologic limits of bone and produces clinically acceptable results.[11,12]

Variations in component design among implant systems may lead to different stress/strain distributions, thus altering the transmission of forces to surrounding bone.[2,13] Most 2-stage external hexagon screw-type implant systems employ abutment screws that can break, loosen, or become distorted because of their small diameter or their design.[14] To avoid this problem, implant-abutment joints with internal hexagons or octagons with increased depths have been proposed and developed.[15,16] A 1-piece taper interference-fit abutment design with a threaded apical terminus is another option.[17] It remains to be investigated whether uneven strain concentrations or screw distortion occur under lateral loading with this system and which of these 2 mechanisms impart greater stability to an implant-supported restoration.

Finite elemental analysis (FEA) is a useful tool for investigating biomechanical interactions of various designs. However, since realistic 3-dimensional (3D) models of the implant-supported prosthesis are complex, many previous studies have altered only a few parameters and have failed to fully exploit the capabilities of FEA.[18,19] The aim of this study was to determine the relative contribution of changes in implant system, position, bone type, and loading condition on the biomechanical response of a single-unit implant-supported restoration using nonlinear 3D FEA.

MATERIALS AND METHODS

Computerized tomographic images of a human edentulous maxillary second premolar area exhibiting buccal bone irregularities were acquired. The size of the edentulous area used was approximately 14 mm in the mesiodistal dimension and 12 mm in the buccolingual dimension. Two types of implants with their respective abutments and restorations (Table 1) were simulated within the bony model (Fig 1) using component dimensions obtained from a previous study.[20] FEA solid models were constructed using Mimics (Mimics 6.1; Materialise Software, Leuven, Belgium) and ANSYS FEA software (ANSYS 8.0; ANSYS, Houston, PA).

The maxillary second premolar crown restoration was simulated by imaging a plaster cast on a scale of 1 to 5 with a 4-axis laser scanner (3D Family Technology, Taipei, Taiwan). Twenty-four profiles in a radial direction from the central fossa of the crown to the root apex were collected in 15-degree increments and assembled as a virtual 3D wire-frame structure with Pro/Engineer (Pro/Engineer 2001; Parametric Technology, Waltham, MA).

The solid crown model was then generated with ANSYS and assembled with the abutments to complete the simulated single-unit implant-supported restoration solid models (Fig 1). The mesh models were generated using a mapping approach with 8-node iso-parametric brick elements (solid 45). Nonlinear frictional contact elements (contact 49; defined as node to surface) were used to simulate the adaptation between the various components of each implant system (Fig 2). A friction coefficient value of 0.5 was assumed for all contact surfaces.[21]

Each implant was modeled at 3 positions within the bony segment. In the first position (P1), implant placement was simulated within the residual ridge parallel to the frontal plane (Figs 1a and 1d). In the second position (P2), implant placement was similar to P1, but there was contact between the implant and the buccal cortical plate in the middle third of the implant body (Figs 1b and 1e). In the third position (P3), implant placement was simulated within the residual ridge, with a buccal angulation of 20 degrees relative to the frontal plane (Figs 1c and 1f). A 20-degree angled abutment was simulated in the P3 position.

Simulations were conducted of each model (Fig 1) with 4 types of bone. These bone types followed the classification of Lekholm and Zarb[22] as follows: *(1)*

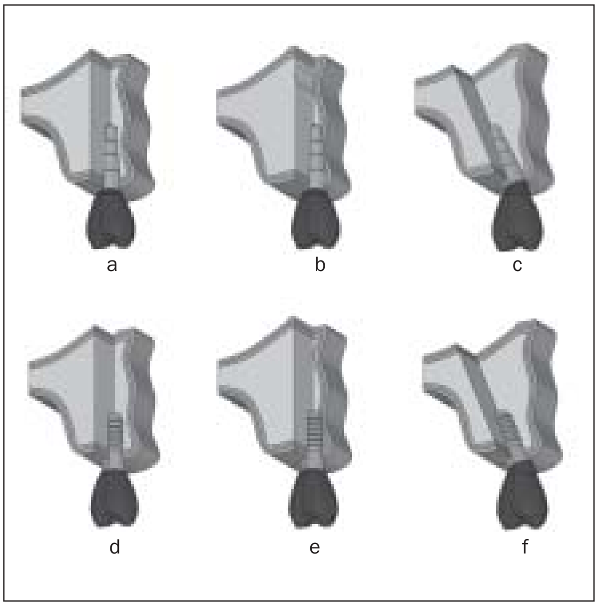


Fig 1 Six solid models showing 2 implant systems, Frialit-2 and Straumann, in 3 positions with fabricated crowns: *(a)* a Frialit-2 implant in position 1 (FRI; P1); *(b)* a Frialit-2 implant in position 2 (FRI; P2); *(c)* a Frialit-2 implant in position P3 (FRI; P3); *(d)* a Straumann implant in position 1 (STR; P1); *(e)* a Straumann implant in position 2 (STR; P2); and *(f)* a Straumann implant in position 3 (STR; P3).

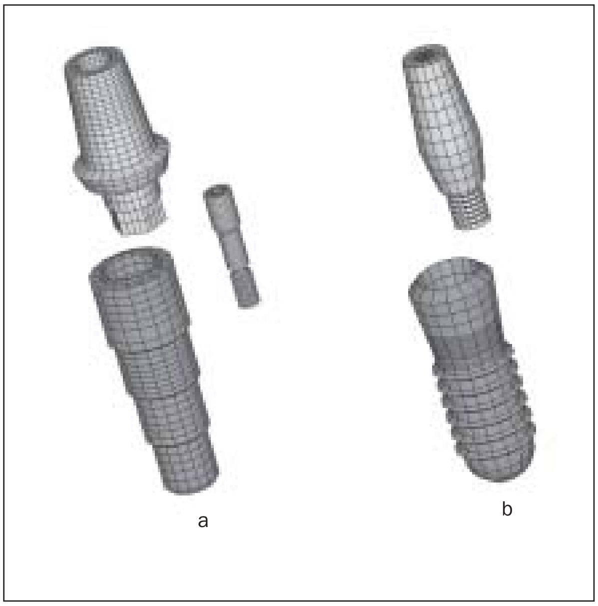


Fig 2 3D FEA models of an implant-supported prosthesis constructed for this study. *(a)* Frialit-2 (FRI) system, including the abutment, abutment screw, and implant. *(b)* Straumann (STR) system, including the abutment and implant.

Table 2 Material Properties Assigned to Materials Simulated

Material	Young's modulus (MPa)	Possion's ratio	References
Cortical bone	14,700	0.3	7
Dense trabecular bone	1,470	0.3	7
Low-density trabecular bone	231	0.3	7
Gold alloy (prosthesis)	90,000	0.3	29, 30
Titanium (implant system)	110,000	0.35	29, 31

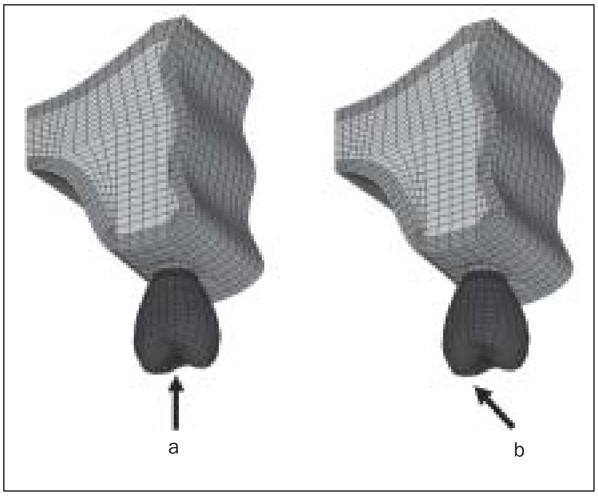


Fig 3 Loading conditions applied *(a)* AF force directed down the long axis of the crown. *(b)* LF concentrated force vector directed at a 45-degree angle relative to the lingual cusp.

entirely homogeneous compact bone, *(2)* 1.5-mm layer of cortical bone bounding a core of dense cancellous bone, *(3)* 0.75-mm layer of cortical bone bounding a core of dense cancellous bone, and *(4)* 0.75-mm layer of cortical bone bounding a core of low-density cancellous bone. Elastic properties used for bone and restorative materials were obtained from the literature (Table 2).

Lateral and axial loading conditions (LF and AF, respectively) were applied to each model (Fig 3). Loading condition LF simulated a lateral 150-N force with a concentrated force vector acting on the lingual cusp at a 45-degree inclination. This force was simulated as approaching the cusp from the buccal direction. Loading condition AF simulated an axially directed 150-N force acting on the central fossa of the crown.[23] Exterior nodes at the mesial and distal surfaces of the alveolar bone were fixed in all directions as the boundary conditions for all 48 models.

Maximum von Mises strain for cortical and cancellous bone was recorded, and maximum von Mises stress was recorded for each implant.[24,25] Effect of implant position, bone quality, implant system, and loading condition on the mechanical response were

Table 3 ANOVA Main Effects for Cortical Bone Strain

Variable	df	SS	Mean SS	%TSS
Position	2	82	41	12
Bone quality	3	64	21	9
Implant type	1	172	172	24
Load condition	1	384	384	55
Total	7	702	234	100

Table 4 ANOVA Main Effects for Cancellous Bone Strain

Variable	df	SS	Mean SS	%TSS
Position	2	165	83	4
Bone quality	3	2692	897	68
Implant type	1	31	31	1
Load condition	1	1091	1091	27
Total	7	3979	1011	100

Table 5 ANOVA Main Effects for Implant Stress

Variable	df	SS	Mean SS	%TSS
Position	2	1882	941	64
Bone quality	3	14	5	0
Implant type	1	924	924	31
Load condition	1	142	142	5
Total	7	2962	1870	100

analyzed using analysis of variance (ANOVA; Minitab 12.23; Minitab, State College, PA).[26] However, because these data from FE analyses have generally been found not to be normally distributed (an essential prerequisite for ANOVA), it was necessary to transform the data prior to performing parametric statistics. Since minimal strain/stress values are preferable, the acquired data were logarithmically transformed using the following equation:

$$n_i = -10\log_{10}(a_i^2)$$

where n_i was the transformed data and a_i was the maximum strain/stress obtained from FEA.[24]

RESULTS

Raw data for maximum von Mises strain (cortical and cancellous bone) and stress (implant) were recorded. Because these data were not normally distributed, a logarithmic transformation was applied. A less negative value in the transformed data corresponds to lower strain/stress. The relative contribution of each effect (sum of squares [SS]) is expressed as a percentage of the total sum of squares (%TSS). SS and %TSS are presented for cortical bone strain (Table 3), cancellous bone strain (Table 4), and implant stress (Table 5). Figure 4 shows magnitude plots for the combined effects of each variable for maximum strain

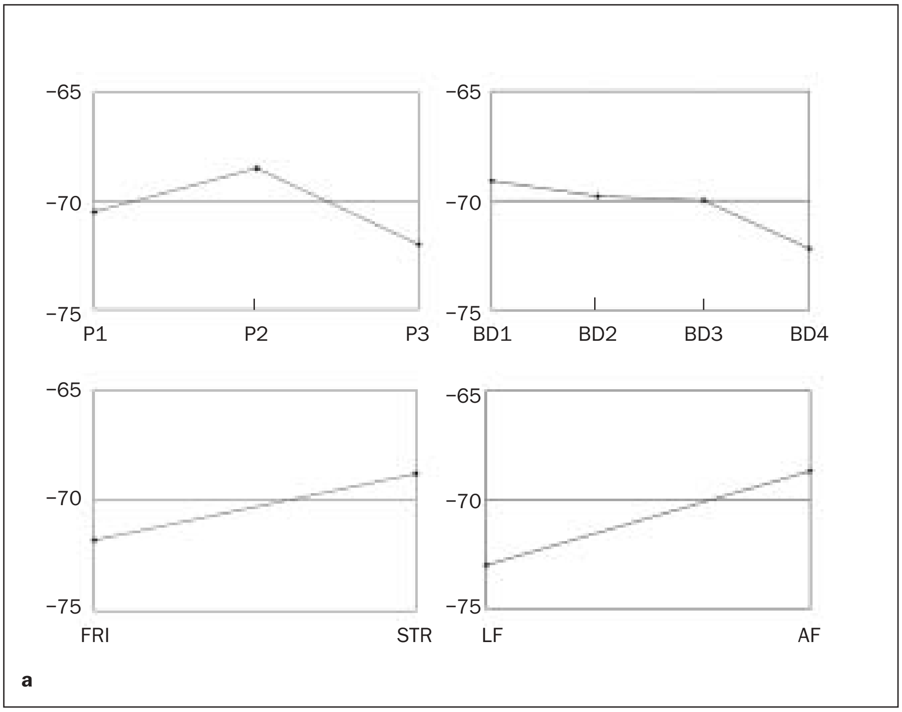
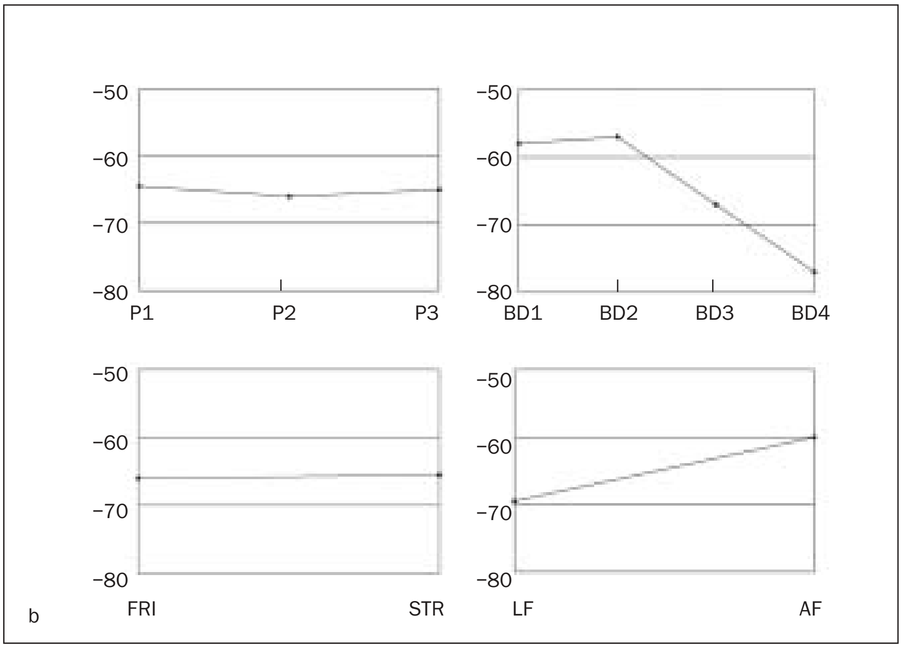
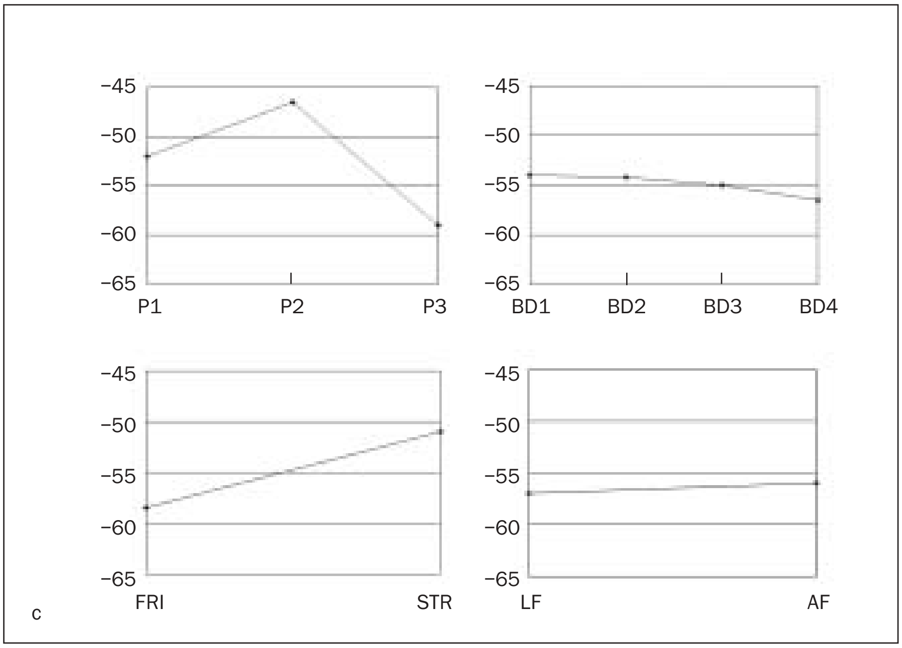


Fig 4 Main effects of implant position (P1, P2, or P3), bone density (1 to 4), implant type (STR or FRI), and loading condition (AF or LF) at each level for transformed maximum von Mises strain on *(a)* cortical bone, *(b, facing page)* cancellous bone, and *(c, facing page)* transformed maximum von Mises stress on the implant.





in cortical bone (Fig 4a) and cancellous bone (Fig 4b) and for maximum stress in the implant (Fig 4c).

With respect to cortical bone (Table 3), loading condition accounted for 55% of the variation in strain magnitude. Implant type accounted for 24% of the variation, implant position accounted for 12% of the variation, and bone quality accounted for 9% of the variation. Figure 4a shows that lateral force and the FRI system showed increased strain when compared with axial force and the STR system, respectively. Implant position was not the major factor affecting strain in cortical bone; however, the plot indicated that P2 resulted in the lowest strain among the 3 positions, followed by P1 and P3. Strain in cortical bone increased with decreasing bone quality.

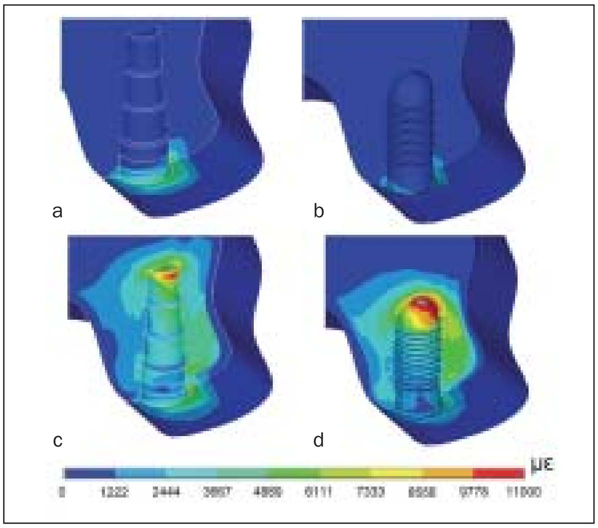


Fig 5 Strain distributions of *(a)* the Frialit-2 (FRI) implant system and *(b)* the Straumann (STR) implant system placed in position 1 with bone type 1 and applied lateral forces. Maximum strain is concentrated at the cervical regions in cortical bone. *(c and d)* The same systems placed in position 1 with bone type 4 and applied lateral forces. Here, maximum strain is concentrated in cancellous bone at the implant apex.

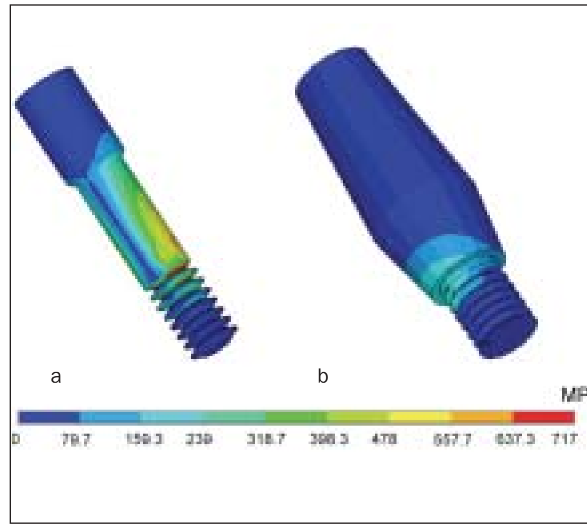


Fig 6 Stress concentration regions of the *(a)* Frialit-2 (FRI) abutment screw and *(b)* the Straumann (STR) solid abutment.

Bone quality (68%) was the major factor affecting cancellous bone strain, followed by loading condition (27%), implant position (4%), and implant type (1%; Table 4). Combined main effects plots showed increasing strain with decreasing bone quality. Lateral force increased strain when compared with axial force. Position and implant type had less effect on cancellous bone strain (Fig 4b).

Stress to the implant was determined primarily by implant position (64%), followed by implant type (31%), loading condition (5%), and bone quality (0%) (Table 5). Combined magnitude plots showed that the P2 position produced lower stress, followed by P1 and P3 (Fig 4c). Also, the STR model reduced stress as compared to the FRI model. Loading condition and bone type demonstrated almost no influence on implant stress.

Areas of strain/stress concentration were determined (Fig 5). Strain concentrations in bone were dependent on bone quality irrespective of loading condition and implant type. The strain distributions in bone types 1 to 3 were similar, with maximum strain concentrated at the cervical regions in cortical bone. The areas of maximum strain with bone type 4 were found in cancellous bone around the apex of the implant. Furthermore, stress concentration regions of the FRI models were found along the threads of the abutment screw. In the STR models, stress concentration regions were found at the tapered end of the abutment and first 2 apical threads of the screw (Fig 6).

DISCUSSION

The successful use of dental implants has been well-documented, but implant failures are still unavoidable.[4,5,27,28] Implant failures observed after prosthesis delivery are mainly related to biomechanical complications. The mechanisms responsible for biomechanical implant failure are not fully understood, owing to complications from many related factors, such as loading condition, prosthesis type, implant design, implant position, bone type, and material properties of the bone-implant interface.[4] Unfortunately, these biomechanical aspects are difficult to investigate using solely clinical or experimental approaches with limited information and sample variations.

FEA has been widely accepted as a complementary tool for understanding detailed mechanical responses in biologic investigations. However, little attempt has been made to assess model sensitivity to variation in input parameters or interactions. Ambiguous results from FEA may occur because of unrealistic assumptions of interfacial conditions between materials and components.[20,21] This study employed 3D FEA coupled with more realistic interfacial conditions (ie, employing a frictional surface between different components and using variable parameters at different levels). A full factorial procedure was performed exploring every possible combination of levels of each factor and the main effect of each level on maximum von Mises strains/stresses.

Strain has been accepted as one of the mechanical signals that stimulates remodeling of the bone surrounding the implant, and von Mises stress has been accepted as the fracture criterion for metal materials based on elastic mechanics.[32–34] This in vitro investigation recorded von Mises strain and stress for bone and implant, respectively, through FEA simulation to assess multiple variables that affect the success of an implant-supported restoration. In addition, ANOVA yielded the contribution of each variable to the total sum of squares and determined the factor levels minimizing stress and strain.

The results indicated that implant position was the primary influence on implant stress; it also contributed to cortical bone strain. The advantage of the P2 position was due to the fact that forces could be transferred into supporting bone by the cervical cortical layer and buccal cortical contact (Fig 1). Implant stress and cortical bone strain concentrations were highest in the P3 position due to a bending moment effect of the angled abutment. These effects indicate that implants should be placed along the direction of axial loading of the proposed prosthesis with multiple areas of cortical contact to obtain a better stress/strain distribution.

Bone quality affected strain for both cancellous (68%) and cortical bone (9%), with strain increasing as bone quality decreased. For bone types 1, 2, and 3, strain concentration regions were found at the cervical areas in cortical bone, due to the higher elastic modulus of cortical bone. With bone type 4, strain increased and was concentrated around the apex due to low bone density. Concentration of maximum strain concentrated around the apical portion of the implant may increase the risk of micromovement and initial instability. When placing implants in sites of lower bone density, the operator is encouraged to place longer or wide-diameter self-tapping implants using a conventional drilling technique without countersinking or to use an osteotome technique without drilling. With the use of such osteocompressive procedures, bone density and primary stability of implants may be improved. Extending the healing period prior to prosthesis fabrication may also increase bone density and yield more favorable force transmission.

The implant model tested affected the strain found in cortical bone and the stress in the implant. Mean values were higher with the FRI model than with the STR model (Figs 4a and 4c). Stress concentration regions seen within the FRI model increase the possibility of mechanical complications such as screw loosening, breakage, or creep. With the STR model, stress concentration regions indicate that the abutment connection relies to a greater extent on contact pressure and frictional resistance of the Morse taper. This effect on the force transmission mechanism supports clinical findings that screw loosening occurs less frequently with the STR model.[17]

Loading condition affected bone strain. The high percentage contribution found in cortical bone was due to the high elastic modulus of this material. Lateral loading produced a bending moment that significantly increased the strain values found at cervical areas in cortical bone and around the implant apex in cancellous bone. Such high strain concentrations induced by unfavorable loading suggest a causative mechanism for marginal bone loss after long-term dynamic loading. This finding supports the recommendation to eliminate or minimize lateral occlusal contacts of posterior implant-supported restorations. Whenever possible, flatter inclines should be developed on cusps, and a cusp-to-fossa relationship in maximum intercuspation with no eccentric occlusal contact should be used. As many anterior teeth and implants as possible should be used to distribute lateral forces if a "group function" occlusal scheme is unavoidable in eccentric movement.

Three-dimensional nonlinear FEA was applied in this study to investigate the relative contribution of changes in implant system, position, bone type, and loading condition on the biomechanical response of a single-unit implant-supported restoration. However, the present investigation was limited by the assumptions made regarding loading condition, material properties, and implant-bone interfacial conditions. Lateral and axial forces were examined separately, whereas clinically, applied forces are usually found to be a combination of both. Linear elastic (homogeneous and isotropic) properties for all materials were used due to numerical convergence considerations and because a wide range of values exist for these properties in the literature. The implant-bone interface was assumed to be fully osseointegrated, and special surface modifications (ie, the SLA surface of the Straumann implant) were not considered. Therefore, the results provide only general insight into the biomechanics of implant loading under average conditions.

CONCLUSIONS

The data from this nonlinear 3D FEA study lead to several conclusions of clinical significance:

1. The placement of implants along the direction of axial loading of the proposed prosthesis may promote better stress/strain distribution.
2. The use of bone condensation methods during placement may improve the initial stability of implants.

3. The STR model (Straumann) may provide a better force transmission mechanism and may decrease the risk of abutment loosening and screw fracture.
4. Establishing an occlusal scheme to reduce lateral occlusal force is recommended.

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REFERENCES

1. Brånemark P-I, Breine U, Adell R, et al. Intra-osseous anchorage of dental prostheses I. Experimental studies. Scand J Plast Reconstr Surg 1969;3:81–100.
2. Adell R, Lekholm U, Rockler B, et al. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. Int J Oral Surg 1981;6:387–416.
3. Zarb GA. Introduction to osseointegration in clinical dentistry. J Prosthet Dent 1983;49:824.
4. Sahin S, Cehreli MC, Yalcin E. The influence of functional forces on the biomechanics of implant-supported prostheses—A review. J Dent 2002;30:271–282.
5. Cehreli MC, Sahin S, Akca K. Role of mechanical environment and implant design on bone tissue differentiation: Current knowledge and future contexts. J Dent 2004;32:123–132.
6. Martinez H, Davarpanah M, Missika P, Celletti R, Lazzara R. Optimal implant stabilization in low density bone. Clin Oral Implants Res 2001;12:423–432.
7. Holmes DC, Loftus JT. Influence of bone quality on stress distribution for endosseous implants. J Oral Implantol 1997;23:104–111.
8. Clelland NL, Gilat A, McGlumphy EA, Brantley WA. A photoelastic and strain gauge analysis of angled abutments for an implant system. Int J Oral Maxillofac Implants 1993;8:541–548.
9. Canay S, Hersek N, Akpinar I, Asik Z. Comparison of stress distribution around vertical and angled implant with finite-element analysis. Quintessence Int 1996;27:591–598.
10. Clelland NL, Lee JK, Bimbenet OC, Brantley WA. A three-dimensional finite element stress analysis of angled abutments for an implant placed in the anterior maxilla. J Prosthet Dent 1995;4:95–100.
11. Sethi A, Kaus T, Sochor P, Axmann-Krcmar D, Chanavaz M. Evolution of the concept of angulated abutments in implant dentistry: 14-year clinical data. Implant Dent 2002;11:41–51.
12. Skalak R. Aspects of biomechanical consideration. In: Brånemark P-I, Zarb GA, Albrektsson T (eds). Tissue-integrated Prostheses: Osseointegration in Clinical Dentistry. Chicago: Quintessence, 1985:117–128.
13. Haas R, Polak C, Furhauser R, Mailath-Pokorny G, Dortbudak O, Watzek G. A long-term follow-up of 76 Brånemark single-tooth implants. Clin Oral Implants Res 2002;13:38–43.
14. Schwarz MS. Mechanical complications of dental implants. Clin Oral Implants Res 2000;11:156–158.
15. Balfour A, O'Brien GR. Comparative study of antirotational single tooth abutments. J Prosthet Dent 1995;73:36–43.
16. Mollersten L, Lockowandt P, Linden LA. Comparison of strength and failure mode of seven implant systems: An in vitro test. J Prosthet Dent 1997;78:582–591.
17. Levine RA, Clem DS, Wilson TG, Higginbottom F, Saunders RL. A multicenter retrospective analysis of the ITI implant system used for single-tooth replacements: Results of loading for 2 years. Int J Oral Maxillofac Implants 1997;12:237–242.
18. Lin CL, Lee HE, Wang CH, Chang KH. Interfacial stress analysis between posterior resin-bonded bridge and abutments by finite element approach. Comput Methods Programs Biomed 2003;72:55–64.
19. Lin CL, Hsu KW, Wu CH. Multi-factorial retainer design analysis of posterior resin-bonded fixed partial dentures: A finite element study. J Dent 2005;33:711–720.
20. Lin CL, Wang JC, Kuo YC. Numerical simulation on the biomechanical interactions of tooth/implant-supported system under various occlusal forces with rigid/non-rigid connections. J Biomech 2006;39:453–463.
21. Merz BR, Hunenbart S, Belser UC. Mechanics of the implant-abutment connection: An 8-degree taper compared to a butt joint connection. Int J Oral Maxillofac Implants 2000;15:519–526.
22. Lekholm U, Zarb GA. Patient selection and preparation. In: Brånemark P-I, Zarb GA, Albrektsson T (eds). Tissue-Integrated Prostheses: Osseointegration in Clinical Dentistry. Chicago: Quintessence, 1985:199–209.
23. Tada S, Stegaroiu R, Kitamura E, Miyakawa O, Kusakari H. Influence of implant design and bone quality on stress/strain distribution in bone around implants: A 3-dimensional finite element analysis. Int J Oral Maxillofac Implants 2003;18:357–368.
24. Frost HM. Wolff's law and bone's structural adaptations to mechanical usage: An overview for clinicians. Angle Orthod 1994;64:175–188.
25. Boresi AP, Schmidt RJ, Sidebottom OM. Advanced mechanics of materials. New York: John Wiley, 1993:136.
26. Dar FH, Meakin JR, Aspden RM. Statistical methods in finite element analysis. J Biomech 2002;35:1155–1161.
27. Gross M, Laufer BZ. Splinting osseointegrated implants and natural teeth in rehabilitation of partially edentulous patients. Part I: Laboratory and clinical studies. J Oral Rehabil 1997;24:863–870.
28. Becker CM, Kaiser DA, Jones JD. Guidelines for splinting implants. J Prosthet Dent 2000;84:210–214.
29. Benzing UR, Gall H, Weber H. Biomechanical aspects of two different implant-prosthetic concepts for edentulous maxillae. Int J Oral Maxillofac Implants 1995;10:188–198.
30. Moffa JP, Lugassy AA, Guckes AD, Gettleman L. An evaluation of nonprecious alloys for use with porcelain veneers. Part I. Physical properties. J Prosthet Dent 1973;30:424–431.
31. van Rossen IP, Braak LH, de Putter C, de Groot K. Stress absorbing elements in dental implants. J Prosthet Dent 1990;64:198–205.
32. Frost HM. Wolff's law and bone's structural adaptations to mechanical usage: An overview for clinicians. Angle Orthod 1994;64:175–188.
33. Mellal A, Wiskott HW, Botsis J, Scherrer SS, Belser UC. Stimulating effect of implant loading on surrounding bone. Comparison of three numerical models and validation by in vivo data. Clin Oral Implants Res 2004;15:239–248.
34. Boresi AP, Shmidt RJ, Sidebottom OM. Advanced Mechanics of Materials. New York: John Wiley & Sons, 1993:130–138.