Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 23 July 2026
Revised 19 Aug 2026
Accepted 06 Sep 2026

Natural Resources for Human Health 2026, Vol. 6 (20s): 879–887

KEYWORDS:
Dental Implants; Dental Stress Analysis; Finite Element Analysis; Short Dental Implants; Subcrestal Placement

Comparison of the Biomechanical Behaviour of Short Dental Implants Placed Equicrestal and Subcrestally in D3 and D4 Bone - FEM Study

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ABSTRACT:

Aim: To investigate the biomechanical performance of short equicrestal and subcrestal implants in D3 and D4 bone by 3D finite element analysis (FEA).

Methods and Materials: In this computational 3D FEA study, four implant configurations (lengths: 6, 7.5 mm; diameters: 4.6, 5.8 mm) in D3 and D4 bone were modelled. The axial and oblique (0°, 15°, 30°) loading of equicrestal and subcrestal (0.5,

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eISSN: 2583-1194

1.0, 1.5, 2.0 mm) placements were investigated. No clinical sampling was done; all models were computational. Groups were defined by bone type (D3 vs. D4), implant diameter, implant length, implant placement depth and loading angle. Von Mises stresses at the bone-implant interface were determined, and statistical analysis used one-way ANOVA with Tukey's HSD post-hoc test.

Results: Stress distribution was significantly related to bone quality, implant diameter, placement depth, and loading angle ($p < 0.05$), but not implant length ($p = 0.1327$). D4 bone showed approximately 30% higher stress than D3 bone (mean difference: −5.83 MPa, $p < 0.0001$). Wider implants (5.8 mm) reduced stress by 25-30% compared with narrower implants (4.6 mm), particularly in D4 bone ($p < 0.0001$). Greatest stress reduction occurred at 0.5 mm subcrestal placement ($p = 0.0154$). Loading angle had the strongest effect ($F = 50.30$) with stress almost doubled at 30°.

Conclusions: The implant diameter and depth of placement can be optimized to partially compensate for compromised bone quality, while the control of the loading direction is still essential. Clinically, in low density bone, wider implants and subcrestal placement of 0.5 mm are preferable with occlusal management to reduce non-axial loading.

INTRODUCTION:

Dental implants are a predictable tooth replacement method with high survival rates of over 90% [1]. However, crestal bone loss is still a concern, particularly in areas of poor bone quality, such as the posterior maxilla [2]. Short dental implants (≤8 mm) have been proposed as a possible alternative to avoid complicated bone augmentation procedures in atrophic ridges [3]. The traditional focus was on implant length as a factor affecting primary stability, however, recent evidence suggests that the diameter and placement depth are more important in influencing the stress distribution at the bone implant interface [4]. Subcrestal placement has been advocated to reduce crestal stress and to preserve marginal bone [5]. Three-dimensional finite element analysis (3D FEA) is an important tool to examine biomechanical behavior under different loading conditions [6].

The literature on short implants and subcrestal placement is increasing, but the evidence of the combined effect of short implants and subcrestal placement on stress distribution in low-density bone (D4) compared with moderate-density bone (D3) is limited. Most previous FEA research has looked at single factors independently, and only a few used a complete factorial design with statistical validation [7]. Therefore, this study was conducted to bridge this gap.

Aim: To compare the biomechanical behaviour of short implants placed equicrestally and subcrestally in D3 and D4 bone using 3D FEA.

OBJECTIVES:

1. To evaluate the effect of implant diameter (4.6 vs 5.8 mm) and length (6 vs 7.5 mm) on von Mises stress distribution.
2. To compare equicrestal and subcrestal placement depths (0.5, 1.0, 1.5, 2.0 mm).
3. To assess the influence of loading angle (0°, 15°, 30°) on stress concentration.
4. To analyze interaction effects between bone quality, implant dimensions, placement depth, and loading angle.

Null Hypothesis (H_0): There is no significant difference in stress distribution at the bone-implant interface in relation to implant diameter, length, placement depth and loading angle in D3 and D4 bone.

MATERIALS AND METHODS:

Study Design

A 3D FEA study was performed to evaluate the biomechanical behavior of short dental implants, placed equicrestally or subcrestally, in D3 and D4 bone. Assuming linear elastic, homogeneous properties, we evaluated the distribution of stresses under static loading.

Bone Model Construction

Two different bone models were created to represent the maxillae:

- **D3 Bone Model:** Anterior central maxillary incisor area with 1 mm uniform cortical layer and moderate-density cancellous bone ([**Insert Figure 1**A).
- **D4 Bone Model:** Posterior maxillary region with 0.5 mm thin cortical layer and low-density cancellous bone ([**Insert Figure 1**B).

[Insert Figure 1 Here]

Implant Configuration

Four implant models were tested (length × diameter × abutment):

- 6 × 4.6 × 3.5 mm
- 7.5 × 4.6 × 3.5 mm
- 6 × 5.8 × 4.5 mm
- 7.5 × 5.8 × 4.5 mm

Each model was tested with equicrestal and subcrestal placement (0.5, 1.0, 1.5, 2.0 mm).

Software and Model Generation

Models were generated in ANSYS Workbench 17.5 (ANSYS, Inc., Canonsburg, PA, USA). Meshing used HyperMesh (Altair Engineering, Inc., Troy, MI, USA) with ten-noded tetrahedron elements (three degrees of freedom per node). Each model had approximately 144,786 elements and 218,725 nodes.

Material Properties

Materials were assumed isotropic, homogeneous, and linearly elastic. Young's modulus and Poisson's ratio were assigned from literature (***Table 1)***.

Table 1. Elastic properties of materials used in the study.

Material	Cortical Bone (D3)	Cancellous Bone (D3)	Cortical Bone (D4)	Cancellous Bone (D4)	Titanium Implant	Titanium Abutment	Zirconia Crown
Young's Modulus (GPa)	13.7	1.37	10.5	0.85	110	110	210
Poisson's Ratio	0.30	0.30	0.30	0.30	0.35	0.35	0.30

Boundary and Loading Conditions

Nodes at the model base were fixed. Complete osseointegration and ideal bone-implant contact were assumed. Loads of 100 N and 200 N were applied at 0°, 15°, and 30°.

Stress Analysis

Von Mises stress was evaluated at the bone-implant interface using ANSYS. Stress distribution was assessed in cortical and cancellous bone for all models (***Table 2***).

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eISSN: 2583-1194

Table 2. Parameters for stress evaluation.

Parameter	Measurement
Implant Placement Depth	Equicrestal and Subcrestal (0.5 mm, 1 mm, 1.5 mm, and 2mm below crest)
Bone Interface	Cortical and Cancellous
Force Magnitude	100 N and 200 N
Force Direction	0°, 15°, and 30°
Stress Evaluation	von Mises stress (MPa)

Data Analysis

Comparison of stress distribution was made according to the bone type, implant dimensions, loading angle and placement depth. Mean stress levels between bone types and implant configurations were compared using a one-way ANOVA statistical analysis. Results are expressed as mean ± SD Significance was indicated with symbols (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$) at $p < 0.05$. Group differences were specified by Tukey's HSD post-hoc test.

RESULTS:

Finite element data were statistically analysed to evaluate the influence of the bone quality, implant diameter, loading angle and placement depth on the stress distribution. No relevant effect of implant length. Detailed results are in Tables 1-3 and Figures 1-3.

ANOVA Results for Individual Factors

One-way ANOVA showed significant effects for bone type ($p < 0.0001$, $F = 18.73$), implant diameter ($p = 0.0008$, $F = 11.45$), placement depth ($p = 0.0061$, $F = 3.72$), and loading angle ($p < 0.0001$, $F = 50.30$). Implant length was not significant ($p = 0.1327$, $F = 2.28$) (Table **3**).

Table 3. One-way ANOVA Results for Different Factors Affecting Stress Distribution.

Factor	Source of Variation	Sum of Squares	df	Mean Square	F-value	p-value
Bone Type	Between Groups	1642.86	1	1642.86	18.73	<0.0001*
	Within Groups	16825.42	192	87.63	-	-
	Total	18468.28	193	-	-	-
Implant Diameter	Between Groups	1039.37	1	1039.37	11.45	0.0008*
	Within Groups	17428.91	192	90.78	-	-
	Total	18468.28	193	-	-	-
Implant Length	Between Groups	217.36	1	217.36	2.28	0.1327
	Within Groups	18250.92	192	95.06	-	-
	Total	18468.28	193	-	-	-
Placement Depth	Between Groups	1345.97	4	336.49	3.72	0.0061*
	Within Groups	17122.31	189	90.59	-	-
	Total	18468.28	193	-	-	-

Loading Angle	Between Groups	6371.55	2	3185.78	50.30	<0.0001*
	Within Groups	12096.73	191	63.33	-	-
	Total	18468.28	193	-	-	-

**Indicates statistical significance ($p < 0.05$)*

Bone Type Comparison

D4 bone showed ~30% higher stress than D3 ($p < 0.0001$; **[Insert Figure 2**A).

Implant Diameter Comparison

Wider implants reduced stress by 25–30% ($p = 0.0008$; **[Insert Figure 2**B).

[Insert Figure 2 Here]

Placement Depth Comparison

Only 0.5 mm subcrestal placement significantly reduced stress compared with equicrestal placement (mean difference: 4.32 MPa; 95% CI: 0.58 to 8.06; $p = 0.0154$). All other pairwise comparisons among subcrestal depths (1.0, 1.5, 2.0 mm) were non-significant ($p > 0.05$). A non-significant trend toward reduced cortical bone stress was observed at 1.5–2 mm (**[Insert Figure 3**A).

Loading Angle Comparison

All pairwise comparisons were significant ($p < 0.001$). The largest difference was between 0° and 30° loading (−10.73 MPa; 95% CI: −13.78 to −7.68), followed by 0° vs 15° (−5.81 MPa) and 15° vs 30° (−4.92 MPa). Stress almost doubled at 30° (**[Insert Figure 3**B).

[Insert Figure 3 Here]

Combined Factor Interactions

Key interactions were clinically relevant. In D4 bone, narrow implants (4.6 mm) caused significantly higher stress than in D3 bone (mean difference: −7.96 MPa; $p < 0.0001$), whereas wider implants (5.8 mm) reduced this difference to non-significance ($p = 0.1061$). In D4 bone, wider implants significantly reduced stress compared with narrow implants (mean difference: 6.92 MPa; $p < 0.0001$), but this diameter effect was not significant in D3 bone ($p = 0.3762$). Subcrestal placement at 0.5 mm was significant in D4 bone (mean difference: 6.32 MPa; $p = 0.0307$) but not in D3 bone ($p = 0.8193$). Oblique loading at 30° was highly detrimental in D4 bone (mean difference: −13.30 MPa; $p = 0.0005$) but not statistically significant in D3 bone ($p = 0.0972$). Overall, wider implants and 0.5 mm subcrestal placement offered greater biomechanical advantage in D4 bone, and non-axial loading had a more pronounced negative effect in low-density bone.

DISCUSSION:

This FEA study assessed short implants in D3/D4 bone under different loads. The stress level of D4 bone was higher than D3 bone, consistent with Sugiura et al., who reported higher stress concentration in low-density bone [8,9]. This is consistent with studies that reported less favourable stress distribution in D4 bone [10,11]. Stress distribution was significantly influenced by implant diameter, with wider implants (5.8 mm) demonstrating less stress than narrower implants (4.6 mm). The diameter effect was significant in D4 bone but not in D3 bone, in agreement with Rungsiyakull et al., who reported a significant diameter effect in D4 bone but not in D3 bone [4,12]. Wider implants are thus beneficial in poor bone quality, in line with Anitua et al. for posterior maxillary regions of poor bone quality and Sindelar et al. for short and ultra-short implants (≤8 mm) [13-15].

No difference was found between 6 mm and 7.5 mm implant lengths. Stress distribution was greatly influenced by placement depth. The 0.5 mm subcrestal placement had the greatest stress reduction compared to equicrestal placement. These findings are supported by additional clinical evidence [5,16-18].

The most important factor was loading angle. Axial loading produced less stress than oblique loading at 30°, demonstrating the significance of occlusal adjustment. Previous FEA studies showed stress to be significantly higher around implants under angled loads, indicating that oblique loading consistently results in higher stress, especially in low-quality bone [4].

Interactions were clinically relevant. When bone type variables are considered, an interaction suggests larger diameters favour weaker bone. The wider implant is more suitable for low-density bone, and 0.5 mm subcrestal placement was significant in D4 bone but not in D3 bone, meaning that depth optimisation is more important in lower-density bone. In D4 bone, there was also a significant interaction with oblique loading, while no interaction was apparent in D3 bone. The results support occlusal management, reduced cantilevers, narrow occlusal tables, and balanced occlusion, particularly in D4 bone.

Schiegnitz and Al-Nawas suggested that wider implants are more appropriate for low-density bone [19]. Al-Johany et al. recommended consideration of site-specific bone characteristics in the selection and technique of implant placement [20].

Diameter had a greater effect than length on optimising biomechanical performance, especially for D4 bone, following Al-Johany et al., who recommended wider, shorter implants for the posterior area. As shown by Sheridan et al., a significant effect was seen on loading angle, and occlusal adjustment and prosthetic design play important roles in reducing non-axial forces; even well-designed implants can fail under unfavourable loading [21].

This research work has certain noteworthy merits. First, it deals with combinations and interactions as previous studies only looked at single factors, in a very large factorial design with different subcrestal depths (0.5, 1, 1.5, 2 mm) and loading angles (0°, 15°, 30°). Second, it is centered on short implants (≤7.5 mm) in low bone quality and demonstrated that the geometric factors most important in reducing stress is the diameter of the implant and not its length. Third, it provides clinically useful data from important interaction effects which have not been quantitatively described, such as better results for wider implants and subcrestal placement in D4 than D3 bone [7,22,23].

The importance of the factors in the bone-implant interface stress distribution is quantitatively found in this investigation. The null hypothesis was not supported for bone quality, implant diameter, depth of placement, and loading angle, but was for implant length. Bone quality, implant diameter, depth of implant placement and most importantly loading angle have a significant impact on biomechanical outcomes. The results indicate that optimizing the diameter and depth of implant placement may be able to overcome poor bone quality and control the direction of loading for the long-term success of the implant.

The current models were based on the premise of complete osseointegration, homogeneous, linear elastic bone and static loading. The modelling of dynamic loading, micromotion and anisotropic remodelling was not carried out. These simplifications may not accurately represent clinical conditions, especially in compromised bone where there may be anisotropic behaviour or remodelling that would influence stress.

Future studies should include dynamic loading and more advanced bone models such as patient-specific anatomy, anisotropic bone modelling, nonlinear material behaviour, screw preload, frictional contact, fatigue and remodelling analysis, uncertainty quantification etc. Further clinical trials are required to verify the best combinations of implant diameter, length and depth of insertion for different bone qualities. There is a need to further investigate macro- and micro-design characteristics of threads (geometry, pitch, depth, surface modification) and new techniques like osseodensifiscation in order to enhance the primary stability in D4 bone.

CONCLUSION:

This study gives quantitative evidence of the relative importance of various factors affecting the stress distribution at the bone-implant interface. Biomechanical outcomes are significantly affected by bone quality, implant diameter, placement depth and especially loading angle. The results suggest that compromised bone quality can be partially compensated by optimizing the implant diameter and the depth of implant placement and that controlling the direction of loading is critical for long-term implant success. These findings may be helpful to clinicians when planning implant treatment under difficult circumstances to make evidence-based decisions.

Future Scope / Clinical Significance

This study offers clinically relevant biomechanical data supporting placement of implants in poor quality bone. The results indicate that the diameter of the implant is more important than its length in atrophic ridges, especially in D4 bone where the highest stress concentration may be found, and that wider diameters should be chosen for treatment. A small 0.5mm subcrestal placement is ideal in terms of stress reduction and surgical simplicity. Occlusal control is still important - oblique loading at 30° nearly doubled the stress values by almost double so decreasing cantilevers, narrowing occlusal tables, and establishing balanced occlusion are important in low-density bone. Future studies should aim to include dynamic loading, anisotropic bone modelling and patient-specific anatomy to increase the predictive value. The results of these computational studies warrant further testing in long-term clinical studies, and they should also be used to explore new techniques like osseodensification for improving primary stability in D4 bone.

List of Abbreviations:

1. 3D = Three-Dimensional
2. ANOVA = Analysis of Variance
3. BIC = Bone-Implant Contact
4. CI = Confidence Interval
5. D3 = Moderate Density Bone
6. D4 = Low Density Bone
7. FEA = Finite Element Analysis
8. FEM = Finite Element Modelling
9. FSA = Functional Surface Area
10. HSD = Honest Significant Difference
11. MPa = Megapascal
12. SD = Standard Deviation

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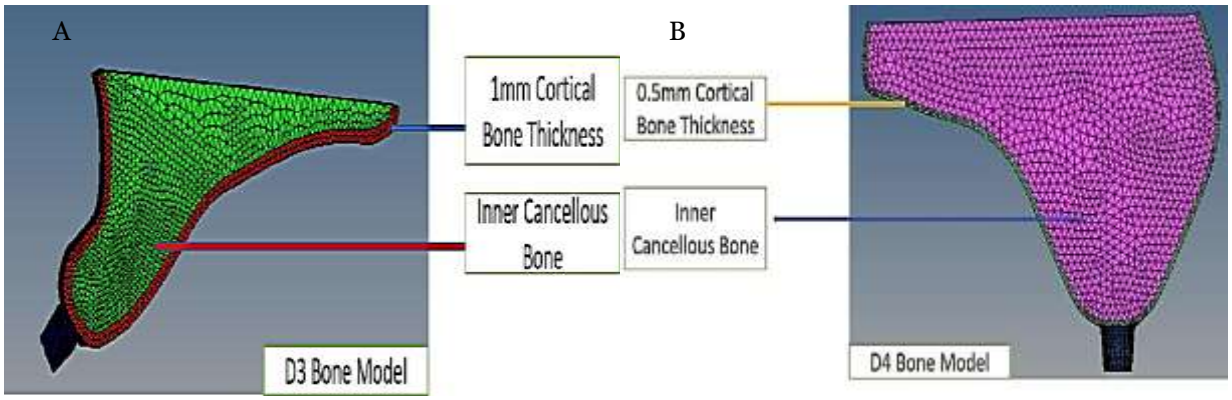


Figure 1. Bone models created using FEM: (A) D3 bone model; (B) D4 bone model.

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eISSN: 2583-1194

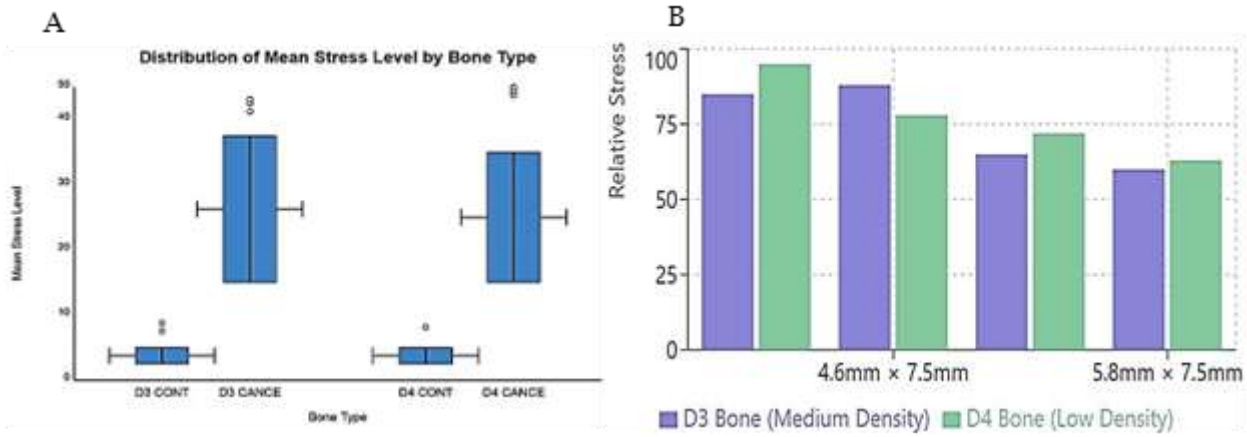


Figure 2. Stress distribution comparisons: (A) D3 vs D4 bone; (B) Implant diameter comparison.

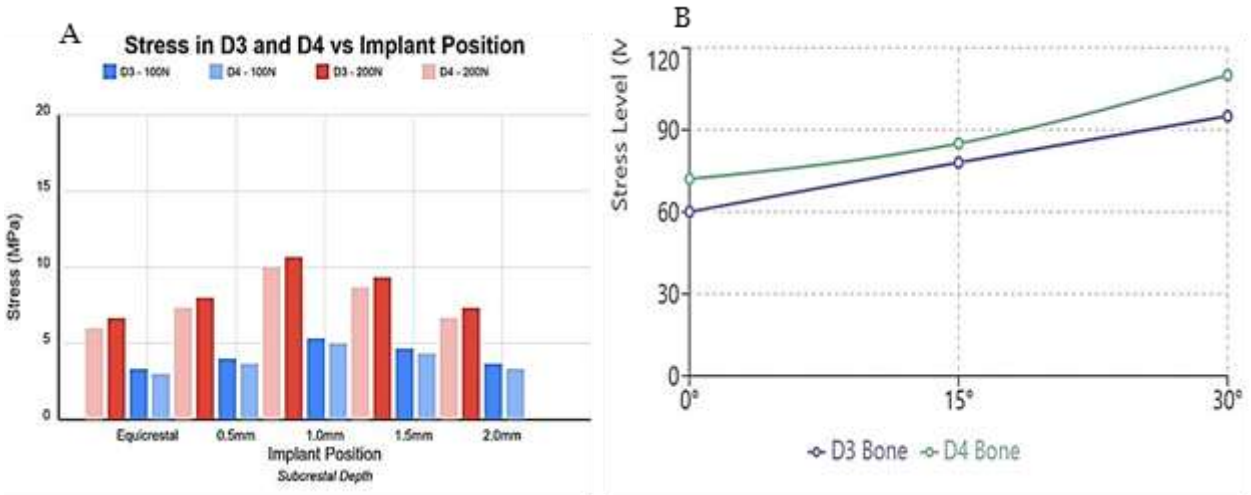


Figure 3. Stress distribution comparisons: (A) Placement depth; (B) Loading angle.