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Finite Element Analysis of TAD Screw Stability in the Mandible: Effects of Marginal Bone Loss and Bone Quality

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ABSTARCT

This study employed finite element analysis to evaluate the effects of marginal bone loss (MBL) and bone quality (BQ) on the stability of temporary anchorage device (TAD) screws in the mandible. A miniscrew placed between mandibular teeth was modeled under a 2 N lateral orthodontic load, and micromotion, stress, and strain were assessed. MBL was simulated by varying cortical thickness from 1 to 3 mm, while BQ was represented by modifying cortical elastic modulus (very weak to very strong). Results showed that reducing cortical thickness increased screw displacement from 1.75 µm to 2.61 µm (~46%), accompanied by elevated cortical strain. In contrast, decreasing bone quality increased displacement from 1.74 µm to 2.27 µm (~30%), with comparatively smaller changes in stress distribution. Across all models, stresses were concentrated at the screw–cortical interface. Findings indicate that cortical thickness has a stronger influence on TAD stability than bone quality, emphasizing the importance of cortical assessment in clinical planning.

Keywords: TAD Screw, Marginal Bone Loss, Bone Quality, Finite Element Analysis, Mandibular Biomechanics

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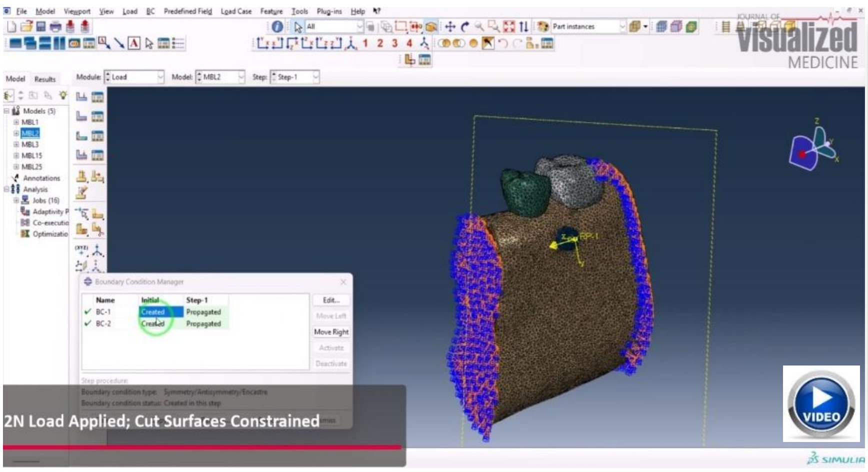

Highlights:

Finite element analysis showed that both marginal bone loss and bone quality affect TAD stability, but cortical thickness has the dominant influence. Cortical thinning significantly increases displacement and strain, with a threshold near 2 mm, while reduced bone quality mainly increases deformation without altering load pathways.

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Temporary anchorage devices (TADs), including miniscrews and miniplates, provide skeletal anchorage independent of patient compliance and enable complex orthodontic movements with minimal invasiveness and immediate loading. They are widely used for molar intrusion, anterior retraction, open-bite correction, vertical control, and impacted tooth management **(1-3)**.

TAD stability depends on mechanical integrity at the bone–implant interface, governed mainly by implant geometry and local bone properties. Under orthodontic loads (0.5–2 N), stresses concentrate in cortical bone, where thread engagement is maximal, influencing micromotion and failure risk **(4-7)**.

Cortical thickness and bone quality are key determinants of stability. Thickness assessed by CBCT correlates with insertion torque, pull-out strength, and micromotion resistance, while trabecular bone plays a secondary role. Marginal bone loss (MBL) reduces cortical support and further compromises stability **(6, 8-10)**. However, the combined effects of cortical loss and bone quality in the mandible remain insufficiently understood, partly due to clinical variability and simplified computational models **(4, 8, 9, 11)**.

Finite element analysis (FEA) enables controlled assessment of these variables by independently varying geometry and material properties while quantifying stress, strain, and micromotion. Accordingly, this study used FEA to evaluate the combined effects of progressive MBL and bone quality on mandibular TAD stability to improve preoperative risk assessment and treatment planning.

2. Protocol

A three-dimensional finite element (FE) model of a mandibular segment containing the second premolar and first molar was developed to evaluate the effects of marginal bone loss (MBL) and bone quality (BQ) on the primary stability of a temporary anchorage device (TAD). The model included cortical bone, cancellous bone, gingiva, and a titanium miniscrew placed interradicularly according to orthodontic guidelines (Figure 1a). The screw geometry represented a standard clinical TAD (1-mm pitch, 8-mm length, 60° thread angle, 6° taper) and was designed in CATIA V5-6 2022 (Figure 1b).

The mandibular geometry was reconstructed from a CT scan of a healthy 30-year-old male using Mimics V21 (Materialise, Belgium).. Five cortical thicknesses (1.0–3.0 mm) simulated progressive MBL, while BQ was modeled by varying cortical Young's modulus around the baseline to generate very strong to very weak conditions (Table 1).

All materials were assumed homogeneous, isotropic, and linearly elastic. Material properties were taken from literature (Table 1), with E = 17.7 GPa for cortical bone, 0.084 GPa for cancellous bone, 0.037 GPa for gingiva, 18.6 GPa for dentin, and 110 GPa for titanium.

Meshing was performed in 3-matic V18 using C3D4 elements. Local refinement was applied at the bone–implant interface. Mesh quality was controlled (skewness ≤0.2), and convergence was achieved when micromotion changes were <5%. Analyses were conducted in Abaqus/Standard 2021 using a quasi-static implicit solver with geometric nonlinearity.

The mandibular base was fully fixed. Bone, teeth, and gingiva were tied, while the screw–bone interface was modeled using surface-to-surface finite sliding contact with hard normal behavior and a friction coefficient of 0.30 **(12)**. A reference point 0.2 mm above the screw head was coupled to the implant, and a 2 N lateral load parallel to the cortical surface was applied under static conditions **(4)**.

Table 1. Material properties used in the FE models.

Structure	E (GPa)	*v*	*ρ* (kg/m³)	References
Mandibular cortical bone (baseline)	17.7	0.30	2000	**(13,14)**
Cortical bone (VS/S/W/VW)	±15%, ±7.5% from baseline	0.30	1900	**(13,14)**
Mandibular cancellous bone	0.084	0.30	1140	**(15)**
Gingiva	0.037	0.45	1000	**(16)**

Structure	E (GPa)	ν	ρ (kg/m³)	References
Teeth (dentin)	18.6	0.31	2100	(17)
Titanium alloy TAD	110	0.34	4430	(4)

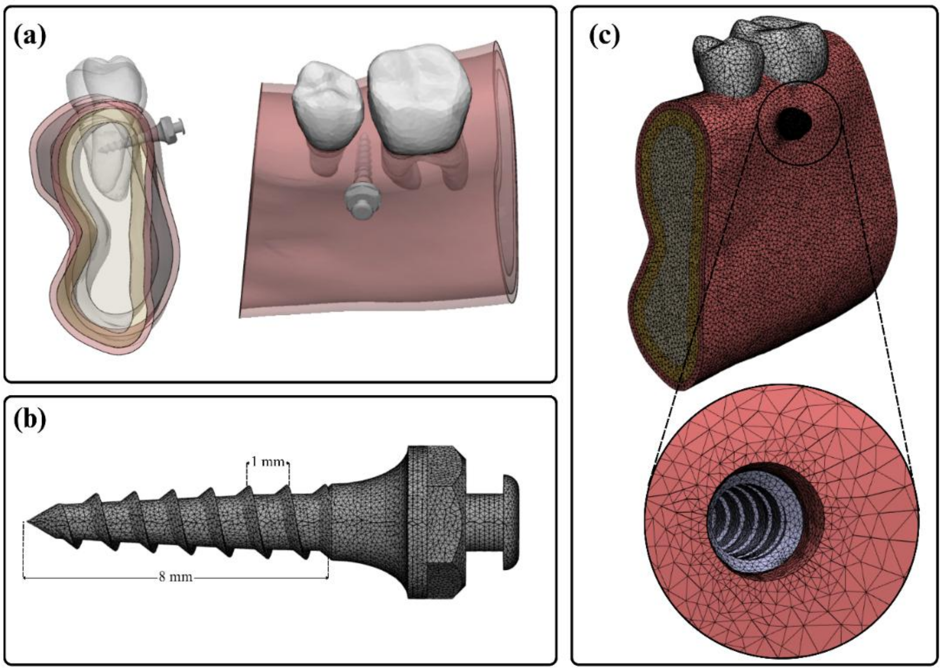

Figure 1. **(a)** TAD placement between teeth 5 and 6, perpendicular to the alveolar bone. **(b)** FE model of the miniscrew with main geometric parameters. **(c)** Complete mandibular FE model including cortical bone, cancellous bone, gingiva, teeth, and screw, with local refinement at the bone–implant interface **(Prepared by Authors, 2025)**.

3. Results and Discussion

The FE results are summarized in Table 2, and stress distributions are shown in Figures 2 and 3. In all models, peak von Mises stresses localized at the screw–cortical interface, while cancellous bone showed negligible stress, confirming that load transfer is predominantly cortical-dominated.

3.1. Effect of Marginal Bone Loss

Cortical thinning substantially affected mechanical response (Figure 2). Screw displacement increased from 1.79 µm (3 mm) to 2.61 µm (1 mm), representing a 46% rise, accompanied by increased cortical strain (0.528–0.694). Screw stress varied between 12.8 and 19.1 MPa, peaking at 2 mm thickness, while cancellous stress remained 1–2 orders of magnitude lower.

Increasing cortical thickness reduced displacement and strain, indicating improved stability; however, effects plateaued beyond ~2 mm, suggesting a threshold beyond which additional cortical support yields limited mechanical benefit.

3.2. Effect of Bone Quality

With cortical thickness fixed at 2 mm, decreasing bone stiffness increased deformation while preserving stress patterns (Figure 3). Screw displacement rose from 1.74 µm (very strong) to 2.27 µm (very weak), and cortical strain increased from 0.393 to 0.616. Stress variation was moderate (14.6–19.7 MPa), and cancellous stresses remained minimal.

3.3. Comparison of MBL and BQ Models

Cortical thickness had a stronger effect on stability than bone quality. MBL increased displacement by ~46%, whereas BQ changes produced ~30% variation. MBL altered both structural stiffness and load transfer, while BQ mainly influenced deformation without changing stress localization. These results indicate cortical geometry is the dominant factor governing immediate TAD stability.

Table 2. Maximum von Mises stress (S), displacement (U), and logarithmic strain (E) in the screw, cortical bone (Cor), and cancellous bone (Can) under marginal bone loss (MBL) and bone quality (BQ) conditions. Stresses are reported in MPa and displacements in mm.

Model	Maximum Von Mises Stress (MPa)			Maximum Displacement (μm)			Maximum Logarithmic μStrain		
	Screw	Cortical	Cancellous	Screw	Cortical	Cancellous	Screw	Cortical	Cancellous
MBL 1	12.8	10.7	0.0827	2.61	0.439	0.430	0.118	0.694	0.931
MBL 1.5	14.1	9.997	0.401	2.19	0.322	0.250	0.135	0.660	0.376
MBL 2	19.1	8.90	0.0320	1.96	0.267	0.145	0.186	0.484	0.278
MBL 2.5	12.8	8.505	0.0472	1.75	0.242	0.0797	0.128	0.516	0.592
MBL 3	13.8	9.495	0.0160	1.79	0.222	0.0508	0.176	0.528	0.484
BQ VS	19.7	9.709	0.03.05	1.74	0.213	0.101	0.193	0.393	0.196
BQ S	19.4	9.303	0.03.12	1.84	0.239	0.120	0.189	0.436	0.231
BQ N	19.1	8.895	0.0320	1.96	0.267	0.145	0.186	0.484	0.278
BQ W	13.7	8.453	0.0330	2.10	0.304	0.180	0.181	0.546	0.392
BQ VW	14.6	8.011	0.0340	2.27	0.347	0.225	0.143	0.616	0.547

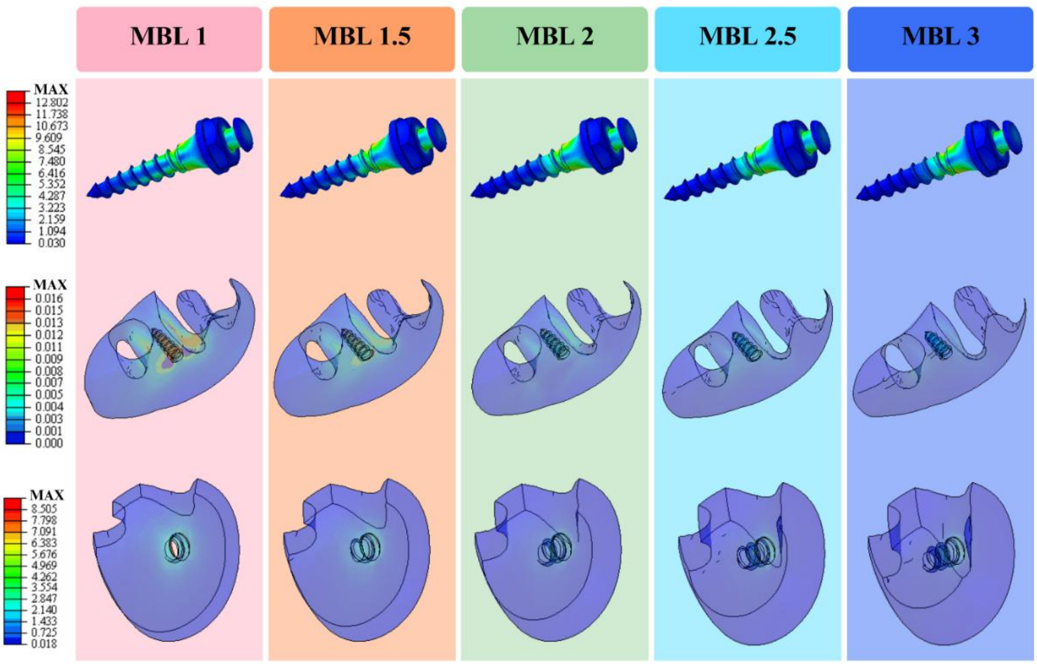

Figure 2. Von Mises stress distribution in MBL models (1–3 mm cortical thickness). Stress is concentrated at the screw–cortical interface, with reduced deformation as cortical thickness increases **(Prepared by Authors, 2025)**.

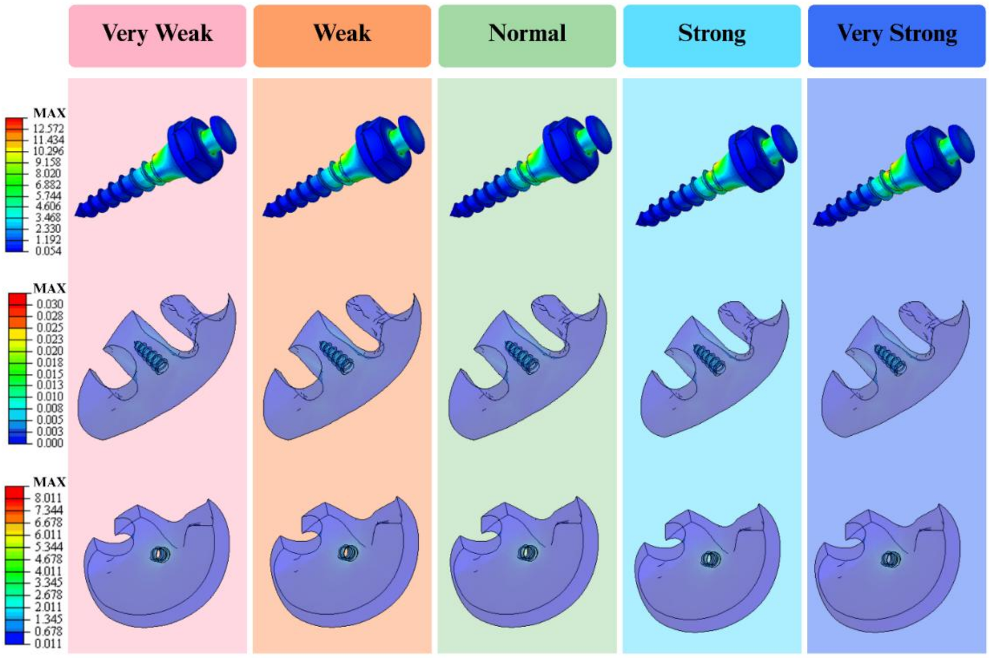

Figure 3. Von Mises stress distribution in BQ models (2 mm cortical thickness) with varying elastic modulus (very weak to very strong). Material stiffness alters stress magnitude and deformation without changing the overall load-transfer pattern **(Prepared by Authors, 2025)**.

The model showed good agreement with previous studies, with ~9% deviation in cortical stress under comparable conditions **(18, 19)**. Trends in displacement and thickness effects were consistent with prior experimental and FE studies **(4, 20-22)**, supporting model reliability.

The model assumes homogeneous, isotropic, linear-elastic materials and static loading. Time-dependent bone remodeling, cyclic fatigue, and biological adaptation were not included. Bone quality was represented only through cortical modulus variation, while trabecular heterogeneity and anisotropy were simplified. Despite these limitations, the assumptions are standard in orthodontic FE analyses and allow controlled isolation of key mechanical variables.

In conclusion, within the limitations of this finite element analysis, both marginal bone loss and bone quality significantly influenced the mechanical stability of temporary anchorage device screws; however, their effects arose through different biomechanical mechanisms. Reduction in cortical thickness produced the largest changes in stress transfer, displacement, and strain, substantially weakening the screw–cortical load-bearing pathway and demonstrating a clear mechanical threshold around 2 mm, below which stability deteriorated markedly. In contrast, variations in bone quality primarily affected deformation behavior, with weaker bone exhibiting increased micromotion and strain but more gradual changes in stress distribution. These findings indicate that geometric loss of cortical support has a stronger impact on global fixation stability than equivalent reductions in material stiffness. Clinically, preserving cortical thickness and accounting for bone quality are both critical for achieving predictable TAD stability, and patient-specific assessment of cortical morphology should be prioritized during treatment planning.

4. Declarations

Acknowledgment

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Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare no conflict of interest, financial or otherwise.

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