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BIOMECHANICAL SENSITIVITY OF A THREE-IMPLANT MANDIBULAR REHABILITATION MODEL UNDER ORTHOTROPIC BONE PROPERTY VARIATIONS: A 3D FINITE ELEMENT STUDY

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ABSTRACT

Most finite element studies of implant-supported mandibular prostheses assume isotropic bone properties, which may not adequately represent the anisotropic mechanical behavior of cortical and cancellous bone tissues. This study aimed to evaluate the biomechanical sensitivity and robustness of a three-implant mandibular rehabilitation model subjected to systematic variations in orthotropic bone material properties using three-dimensional finite element analysis. Using Ti-6Al-4V material, implants were shown; the bone was defined with orthotropic linear-elastic properties. Orthotropic Young's modulus and shear modulus were systematically varied by −15%, −10%, −5%, +5%, +10%, and +15% relative to the baseline model. Under a 100 N axial load, biomechanical reactions including von Mises stress, principal strain, and displacement were studied with variation coefficients employed to evaluate their consistency. The results demonstrated that stress responses remained relatively stable across all orthotropic variations, with coefficients of variation (CV) ranging from 0.21% to 2.35%. In contrast, strain exhibited the highest sensitivity, particularly in cortical and cancellous bone, with CV values of 10.30% and 10.19%, respectively. Cortical bone strain decreased by approximately 27.1%, while cancellous bone strain decreased by 26.6% as orthotropic stiffness increased from V1 to V7. Displacement also decreased by approximately 26%, indicating improved structural stability with increasing bone stiffness. Young's modulus had a greater influence than shear modulus, and increasing stiffness reduced total displacement. Still, the three-implant system showed consistent load distribution patterns, which suggested strong biomechanical stability. These findings underline how important bone flexibility is for the dynamics of peri-implant tissue and support the application of strain-related metrics for estimating implant placements.

Keywords: finite element modeling; dental implants; orthotropic bone properties; sensitivity assessment; mandibular reconstruction.

INTRODUCTION

Tooth loss significantly hampers masticatory function and adversely impacts oral health–related quality of life, diminishing the physical condition, psychological well-being, and socializing capacity of an individual (Tabita et al., 2024). Implant-supported rehabilitation has emerged as a preferred treatment option for edentulous patients because it provides superior prosthesis retention and stability, improves chewing efficiency, and results in higher levels of patient satisfaction compared with conventional removable dentures (Froimovici et al., 2024).The long-term success of implant-supported prostheses depends on successful osseointegration, adequate peri-implant hard and soft tissue conditions, and the restoration of oral function and patient well-being (Feng et al., 2025; Linn et al., 2024).

Distribution of stress, strain, and displacement in the implant–bone complex is an important factor that influences implant stability and the long-term success of implant-supported prosthesis rehabilitation (D. Alemayehu, 2021; Ceddia et al., 2025; Kriswanto, Jamari, Andika, et al., 2025; Nabil et al., 2024). Biomechanical response in the implant–bone complex is an important factor that influences implant stability and the long-term success of implant-supported prosthesis rehabilitation (D. Alemayehu, 2021; Ceddia et al., 2025; Lin et al., 2022). Therefore, understanding the biomechanical response of implant systems to variations in bone material properties is important because these properties significantly affect stress distribution and implant performance (D. Alemayehu, 2021; Ceddia et al., 2025).

Finite Element Analysis (FEA) is extensively utilized in implant dentistry as a computational approach for evaluating stress distribution and structural deformation within implant-supported systems. Its application is particularly valuable in biomechanical investigations where direct experimental observation is difficult or impractical (D. Alemayehu, 2021; Ceddia et al., 2025). Previous studies have applied FEA to investigate the effects of implant geometry, bone quality, loading conditions, and bone material properties on the biomechanical performance of dental implant systems (D. Alemayehu, 2021). Despite its extensive application, many existing studies continue to model bone as an isotropic, homogeneous, and linearly elastic material, an assumption that may not fully reflect the complex nature of biological tissues (D. Alemayehu, 2021). The use of homogeneous material assumptions simplifies the heterogeneous nature of bone and may reduce the representativeness of finite element predictions (Barteld et al., 2021).

Physiologically, the mandibular bone exhibits anisotropic behavior, meaning that its mechanical properties are not the same in all directions (Barteld et al., 2021). An orthotropic material assignment assumes that the bulk material properties are not the same in all directions (Barteld et al., 2021; Ceddia et al., 2025). Previous studies have demonstrated that anisotropic or orthotropic constitutive formulations can significantly influence the predicted stress and strain fields in finite element analysis (Karabelas et al., 2021).

Although some studies have evaluated stress distribution in models with different implant configurations (Aalaei et al., 2023). Currently, little is known about the sensitivity of various implant materials to stress distribution in the peri-implant area under chewing loads (Matta et al., 2024). Bone mechanical properties are influenced by factors such as bone quality, age-related changes, anatomical site, and specimen-specific differences, highlighting the need for heterogeneous material modeling in finite element analyses (Soodmand et al., 2024). The variation has the potential to affect the biomechanical response of the implant system used in clinical practice (D. B. Alemayehu et al., 2024).

Sensitivity analysis can be used to examine how assumptions and material parameters influence the accuracy and results of finite element models (Soodmand et al., 2024). The sensitivity approach is conducted to investigate the effect of variations in the friction coefficient and Young's modulus (Sim et al., 2025). Therefore, sensitivity analysis is a relevant approach for identifying the most influential parameters in the biomechanical behavior of implant-supported prostheses and evaluating the effects of geometric parameters on biomechanical outputs (Hosseini-faradonbeh & Katoozian, 2022; Wirthl et al., n.d.). In addition, robustness evaluation can be performed to assess the system's ability to maintain stable biomechanical response patterns despite variations in material parameters (Hussein et al., 2023; Liu et al., n.d.; Wirthl et al., n.d.).

Although finite element analysis has been extensively employed to investigate the biomechanical behavior of implant-supported prostheses, most previous studies have primarily focused on implant geometry, loading conditions, or bone quality while assuming isotropic material properties for cortical and cancellous bone. Although several investigations have incorporated anisotropic or orthotropic constitutive models, these studies have largely emphasized stress distribution rather than evaluating the sensitivity of multiple biomechanical responses to systematic variations in orthotropic material properties. Consequently, the extent to which uncertainty in bone elastic properties influences stress, strain, and displacement within implant-supported prostheses remains insufficiently understood, particularly for simplified three-implant mandibular rehabilitation systems.

Furthermore, previous studies rarely distinguish the relative biomechanical contributions of Young's modulus and shear modulus or assess the robustness of implant systems against physiological variations in orthotropic bone properties. This limitation restricts the clinical interpretation of finite element predictions because bone mechanical properties vary substantially among patients due to differences in bone density, anatomical location, aging, and pathological conditions.

To address these knowledge gaps, the present study systematically evaluates the biomechanical sensitivity of a three-implant mandibular rehabilitation model subjected to controlled variations in orthotropic cortical and cancellous bone properties. In addition to quantifying stress, strain, and displacement responses, this study evaluates biomechanical robustness using the coefficient of variation (CV) and independently examines the relative influence of Young's modulus and shear modulus. These approaches provide a more comprehensive understanding of patient-specific material uncertainty and contribute to the development of more clinically representative finite element models for implant-supported rehabilitation.

METHODS

This study is a computational biomechanical study based on three-dimensional finite element analysis (3D-FEA) designed to evaluate the sensitivity of the biomechanical response of implant-supported prosthesis systems to variations in the orthotropic material properties of the mandibular bone.

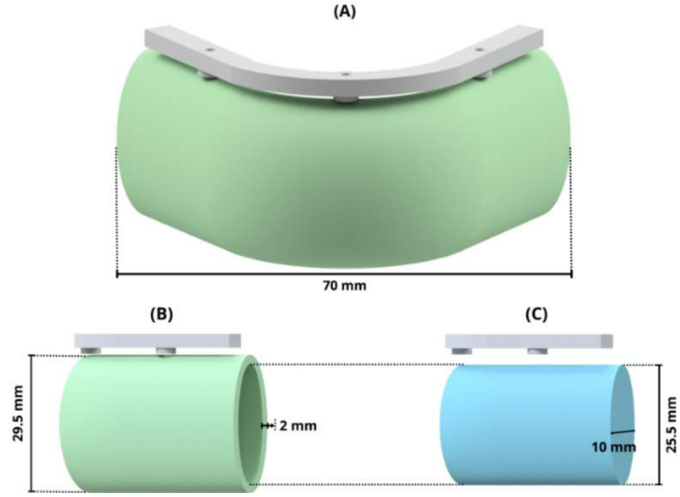

Figure 1. Full Mandibular Geometrical Bone Block Modeling; (A) Full mandibular bone-block; (B) Cortical bone; (C) Cancellous bone. All dimensions are in millimeters (mm); The model is generated at a 1:1 scale.

The geometric model is developed from a simplified full edentulous mandibular representation into a cortical–cancellous bone block model. This model consists of a cortical bone layer and a cancellous bone core. This approach was chosen because it has been widely used in finite element studies to evaluate the biomechanical response of implants (Soodmand et al., 2024). Although it does not fully capture the complexity of mandibular anatomy, this approach is considered adequate for evaluating the relative influence of variations in material parameters on the biomechanical response of the implant–bone system.

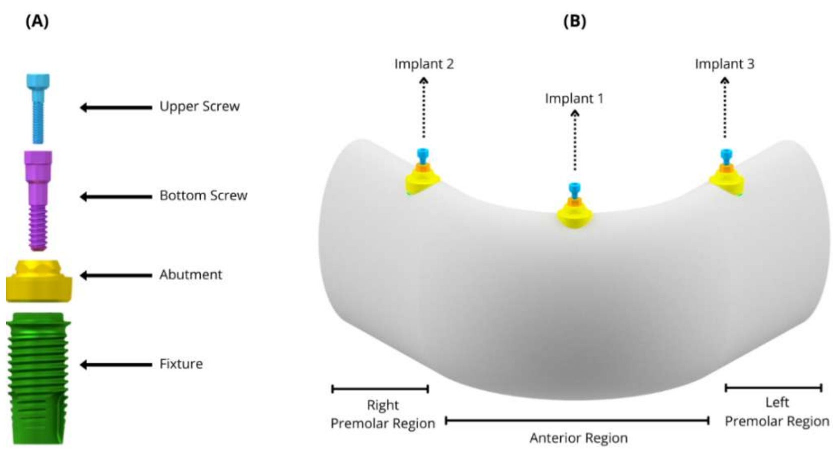

Figure 2. Implant Configuration System; (A) Implant Component; (B) Implant Placement Configuration.

The implant system comprises a fixture, an abutment, an upper screw, and a lower screw with a buttress thread, all having constant geometrical proportions throughout the simulation. The fixture has a diameter of 5 mm and a length of 10 mm. The rehabilitation configuration includes three implants placed symmetrically in one anterior region and two bilateral premolar regions. The three-implant configuration was chosen as a simplified yet clinically relevant rehabilitation scenario to isolate the influence of material properties (BAKİ et al., 2025a). All implant–bone interfaces are assumed to undergo complete osseointegration and are modeled as bonded contact to represent the ideal biological integration condition.

Table 1. Material properties

Component of Model	Young's Modulus (GPa)	Shear Modulus (GPa)	Poisson's Ratio	Reference
Cortical Bone	$E_x = 12.7$	$G_{xy} = 5.5$	$\nu_{xy} = 0.31$	(Ding et al., 2014)
	$E_y = 22.8$	$G_{yz} = 7.4$	$\nu_{yz} = 0.28$	
	$E_z = 17.9$	$G_{xz} = 5$	$\nu_{xz} = 0.18$	
Cancellous Bone	$E_x = 0.511$	$G_{xy} = 0.434$	$\nu_{xy} = 0.31$	(Ding et al., 2014)
	$E_y = 0.907$	$G_{yz} = 0.081$	$\nu_{yz} = 0.3$	
	$E_z = 0.114$	$G_{xz} = 0.078$	$\nu_{xz} = 0.22$	

Finite element simulations were performed in ANSYS Workbench 2023 R1 using a workstation equipped with an 11th Generation Intel® Core™ i5-1135G7 processor and 8 GB of RAM. The implant assembly was assumed to be a homogeneous, isotropic, and linearly elastic structure and was assigned the material properties of Ti-6Al-4V (Grade 5) alloy, including a Young's modulus of 113.8 GPa and a Poisson's ratio of 0.342. These material properties were obtained from the database (MatWeb, n.d.) Cortical and cancellous bone were modeled as homogeneous orthotropic materials exhibiting linear elastic behavior to represent their distinct mechanical responses in the longitudinal, transverse, and radial directions (Bazyar et al., 2023). The orthotropic material model was characterized by nine independent elastic constants, comprising three elastic moduli (Ex, Ey, and Ez), three shear moduli (Gxy, Gyz, and Gxz), and three Poisson's ratios (νxy, νyz, and νxz). The material property values are adopted from a mandibular orthotropic dataset that has been widely used and validated in previous finite element studies (Ding et al., 2014).

Based on these reference values, a sensitivity analysis was conducted to evaluate the influence of variations in orthotropic properties on the biomechanical response of the implant-bone system. The baseline model (*V4*) used the reference material properties. At the same time, variations of ±5%, ±10%, and ±15% were applied simultaneously to Young's modulus and shear modulus to represent the uncertainty in the mechanical properties of bone reported in the literature (Öhman-Mägi et al., 2021; Osterhoff et al., 2017; Zhang et al., 2024). In addition, two scenarios are used to isolate the influence of each parameter Young's modulus with a constant shear modulus (V8) and shear modulus variation with a constant Young's modulus (V9).

Table 2. Orthotropic Variation Groups

Variation	Young's Modulus (%)	Shear Modulus
V1	-15%	-15%
V2	-10%	-10%
V3	-5%	-5%
V4	Baseline	Baseline
V5	5%	5%
V6	10%	10%
V7	15%	15%
V8	E Increased	G constant
V9	G increased	E constant

The selected variation was intended to represent the heterogeneity of bone mechanical properties, which has been reported to depend on bone density, anatomical site, specimen-specific differences, and individual factors such as age and sex (Soodmand et al., 2024). With this approach, the model's sensitivity to changes in orthotropic properties can be systematically evaluated without assuming a single material value to represent the entire population.

All models are discretized using three-dimensional tetrahedral elements. Local refinement is applied to areas expected to experience high stress gradients, including the implant thread, the implant–bone interface, and the peri-implant cortical bone.

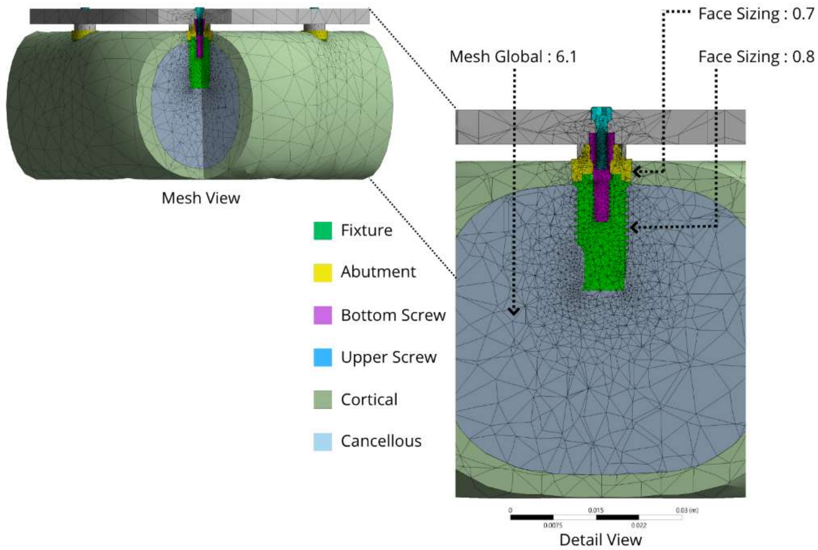

Figure 3. Finite Element Mesh Configuration and Local Refinement Around the Implant–Bone Interface

Numerical verification was conducted through mesh convergence analysis to ensure solution independence from mesh density. The final finite element model consisted of 401,250 nodes and 266,637 tetrahedral elements. Convergence was considered achieved when the variation in all evaluated biomechanical parameters remained below 5% between successive mesh refinement levels. The selected mesh configuration (element size = 6.1 mm) satisfied this criterion and was therefore used for all subsequent simulations.

Table 3. Mesh convergence based on stress stabilization

Element Size	N	E	σvM Max				σ1Max	
			Fixture	Upper	Screw	Abutment	Cortical	Canceloous
5.9	402201	267353	9.5477	17.389	41.612	41.897	4.5221	0.39231
6.0	401775	267030	9.5494	17.389	41.612	41.9	4.4526	0.39306
6.1	401250	266637	9.5439	17.399	41.873	42.012	4.6704	0.39231

Note: n = number of nodes; e = number of elements; σvM = maximum von Mises stress; σ1 = maximum principal stress. All stress values are expressed in MPa. Cortical and cancellous denote the cortical and cancellous bone regions, respectively.

Model validation was performed qualitatively by comparing the stress distribution pattern with findings reported in previous finite element studies of mandibular implant-supported prostheses. Consistent with previous investigations, stress concentrations were predominantly localized around the implant neck, implant–abutment connection, and peri-implant cortical bone region. These observations indicate that the developed model provides biomechanically realistic predictions and is suitable for orthotropic sensitivity analysis.

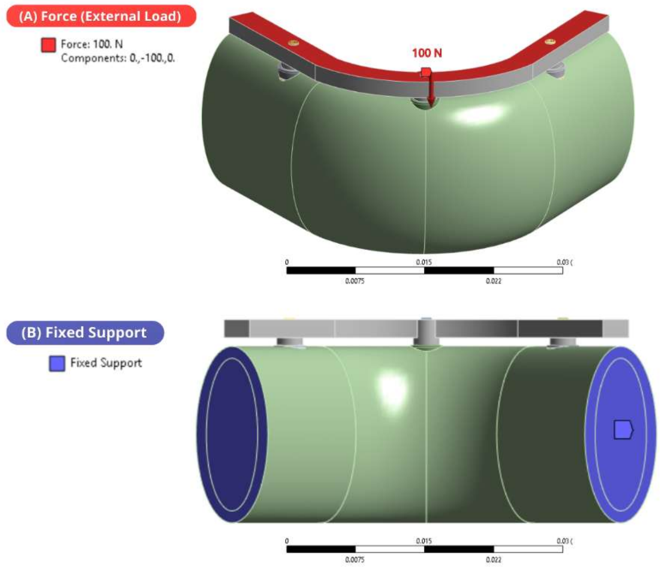

Figure 4. Boundary conditions applied to the finite element model; (A) Force; (B) Fixed Support

Boundary conditions are applied by providing fixed supports at both ends of the mandibular bone-block model to restrict all translations and rotations. All contacts between implant components and the implant–bone interface are considered bonded contacts. The loading consists of an axial force to isolate the effect of the orthotropic material property variations on the biomechanical response without being influenced by additional shear components that appear under oblique loading. A static load of 100 N is applied along the implant's longitudinal axis through the upper screw area as the prosthetic load transmission (Figure 4). The value of 100 N was chosen because it falls within the range of physiological masticatory loads commonly used in finite element studies of mandibular implants (BAKİ et al., 2025b).

The biomechanical parameters evaluated include von Mises stress, principal strain, and total displacement across all system components, including the implant, abutment, upper screw, bottom screw, cortical bone, and cancellous bone. Expressed as the percentage variation in biomechanical parameters for every material variation, biomechanical sensitivity is computed as the relative shift from the baseline model. The percentage change with respect to the baseline model (*V4*) is calculated using equation (1):

$$\%\Delta = \frac{X_i - X_{baseline}}{X_{baseline}} \times 100$$

Using the coefficient of variation (CV) and computed with equation (2), the degree of fluctuation in biomechanical reactions was evaluated.

$$CV = \frac{SD}{Mean} \times 100\%$$

The Coefficient of Variation (CV) shows how stable biomechanical responses are when there are changes in orthotropic material properties. Basically, a lower CV means the responses tend to be more consistent.

Because this research uses a deterministic finite element-based simulation, inferential analysis was not conducted. All results are analyzed descriptively using mean values, standard deviations, percentage changes, and coefficients of variation to identify patterns in biomechanical sensitivity and the implant's system stability response.

RESULTS AND DISCUSSION

3.1 Mesh Verification

Mesh convergence analysis was conducted to ensure that the biomechanical responses were not influenced by the element size used in the numerical discretization. The evaluation results showed that all observed biomechanical parameters met the convergence criteria with deviations of less than 5% at the final mesh level (Table 4). The greatest variation was observed in the cortical bone, while the implant component showed relatively minimal changes with the mesh refinement process.

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Table 4. Convergence Status of the Finite Element Model Across Mesh Levels

Element Size	Percentage Difference (%)						Convergence Status
	Fixture	Upper	Screw	Abutment	Cortical	Cancellous	
5.9 mm	-0.01%	0.02%	-0.01%	-0.04%	12.44%	6.00%	Not Convergent
6.0 mm	0.02%	0.00%	0.00%	0.01%	-1.54%	0.19%	Convergent
6.1 mm	-0.06%	0.06%	0.63%	0.27%	4.89%	-0.19%	Convergent

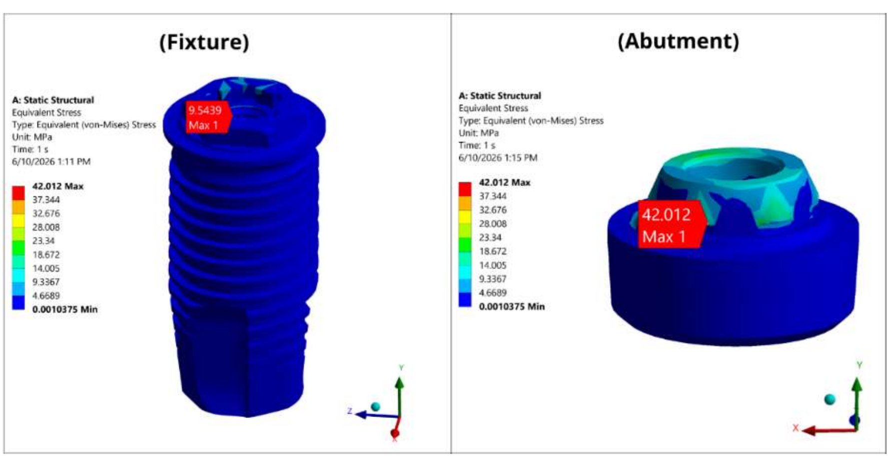
Considering numerical accuracy and computational efficiency, the 6.1 mesh level was chosen because it provides a more stable representation of cortical bone response while maintaining reasonable computational efficiency. Thus, the simulation results in this study are considered to have an adequate level of numerical reliability, as the von Mises stress is less than 0.5%.

3.2 Influence of Orthotropic Properties on Stress Distribution

The baseline orthotropic model (V4) produced von Mises stresses of 9.5439 MPa in the fixture, 17.399 MPa in the upper screw, 41.873 MPa in the bottom screw, and 42.012 MPa in the abutment, while the corresponding principal stresses were 4.6704 MPa and 0.3923 MPa in cortical and cancellous bone, respectively (Table 5). Across the orthotropic variation groups, stress responses remained relatively stable despite systematic changes in material stiffness. From V1 (−15%) to V7 (+15%), abutment stress decreased from 43.850 MPa to 40.788 MPa (7.0%), whereas cortical bone stress decreased only from 4.7375 MPa to 4.6634 MPa (1.6%). The coefficient of variation further confirmed the robustness of stress responses, with CV values ranging from only 0.21% to 2.35% across all evaluated components. These quantitative results demonstrate that stress transfer within the three-implant mandibular rehabilitation system was only minimally affected by orthotropic material variations.

Table 5. Baseline Stress Response of Orthotropic Reference Model (*V4*)

Implant Component	Output (MPa)
Fixture von Mises stress	9.5439
Upper screw von Mises Stress	17.399
Bottom screw von Mises stress	41.873
Abutment von Mises stress	42.012
Cortical Principal stress	4.6704
Cancellous Principal stress	0.39231



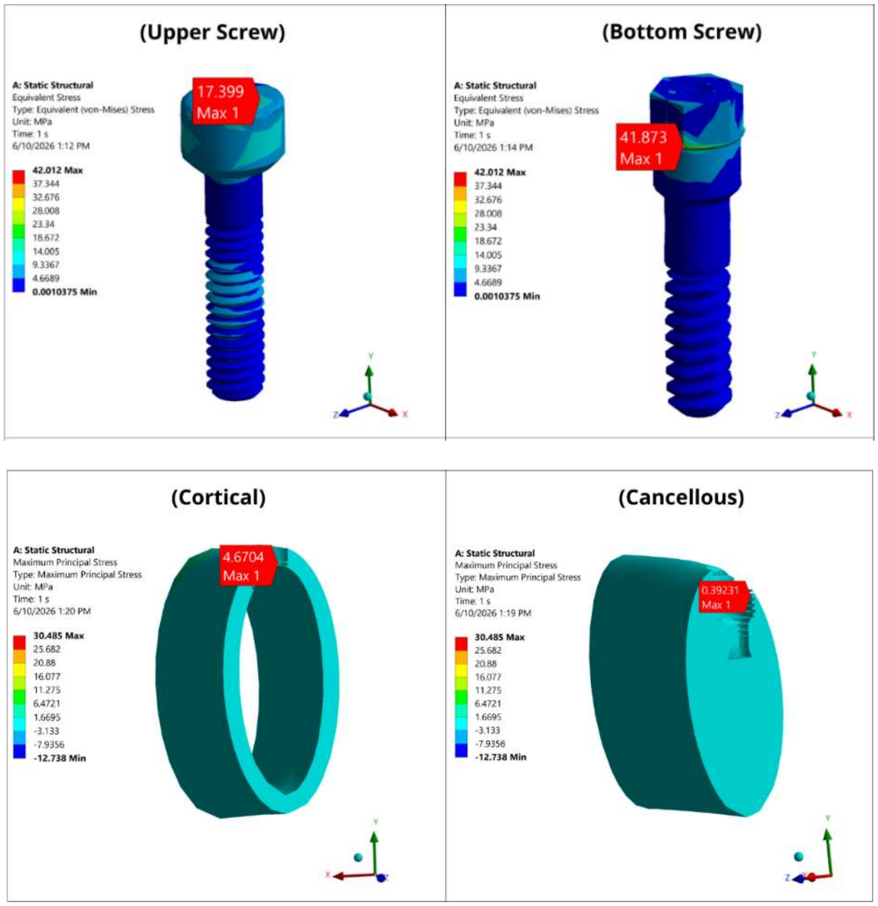


Figure 5. Von Mises stress distribution in implant components and principal stress distribution in cortical and cancellous bone for the baseline orthotropic model (*V4*).

Table 6. Von Mises Stress and Principal Stress Under Orthotropic Variations

Variasi	σvonF (MPa)	σvonU (MPa)	σvonB (MPa)	σvonA (MPa)	σCt (MPa)	σCn (MPa)
1	9.4751	17.339	42.182	43.85	4.7375	0.40089
2	9.4579	17.31	42.151	43.192	4.7257	0.39814
3	9.4395	17.284	42.123	42.606	4.7149	0.39552
4	9.5439	17.399	41.873	42.012	4.6704	0.39231
5	9.4028	17.239	42.073	41.607	4.689	0.39037
6	9.3838	17.219	42.051	41.178	4.677	0.38797
7	9.3651	17.201	42.031	40.788	4.6634	0.38545
8	9.3801	17.247	42.073	41.756	4.858	0.38531
9	9.4261	17.233	42.075	41.5	4.5314	0.39565

From a biomechanical standpoint, this behaviour can be explained by the fact that stress distribution is primarily governed by equilibrium conditions, external loading, structural geometry, and boundary constraints rather than by material stiffness alone. Under a constant axial load of 100 N, increasing Young's modulus mainly reduces structural deformation without substantially altering the load-transfer pathway throughout the implant–bone complex. Consequently, stress redistribution remains relatively stable despite changes in orthotropic elastic properties.

This mechanical behaviour is consistent with Hooke's constitutive relationship ($\sigma = E\varepsilon$), where an increase in elastic modulus primarily decreases strain while maintaining a comparable stress state under identical loading conditions. Therefore, changes in orthotropic stiffness are reflected more prominently in deformation-related parameters than in stress distribution.

These findings are consistent with those reported by (Yang et al., 2023), who demonstrated that deterioration of bone mechanical properties increased peri-implant stress only slightly, whereas the overall stress concentration remained localized around the implant neck and cortical bone. Similarly, the present study indicates that the three-implant configuration preserves a stable stress-transfer mechanism despite variations in orthotropic material properties.

From a clinical perspective, the limited sensitivity of stress suggests that stress alone may not be sufficiently sensitive for evaluating patient-specific changes in bone quality. Instead, stress analysis should be interpreted together with strain and displacement to provide a more comprehensive biomechanical assessment during implant treatment planning.

3.3 Influence of Orthotropic Properties on Strain Distribution

Strain exhibited substantially greater sensitivity to orthotropic material variations than stress. Cortical and cancellous bone strains showed coefficients of variation of 10.30% and 10.19%, respectively, approximately four to five times higher than those observed for stress responses (0.21–2.35%). These results indicate that strain was approximately four to five times more responsive to orthotropic material variations than stress, highlighting its superior capability for detecting biomechanical changes associated with alterations in bone stiffness.

Increasing orthotropic stiffness from V1 to V7 reduced cortical bone strain from 2.91×10^{-4} to 2.12×10^{-4} (27.1%) and cancellous bone strain from 7.43×10^{-4} to 5.45×10^{-4} (26.6%). In contrast, strain variations within the implant components remained below approximately 7%, indicating that the surrounding bone tissue was considerably more responsive to changes in orthotropic stiffness than the metallic implant components. This behavior can be explained by the inverse relationship between material stiffness and deformation. According to Hooke's law ($\varepsilon = \sigma/E$), strain is directly governed by the elastic stiffness of the surrounding bone. Under a relatively constant stress state, increasing Young's modulus proportionally reduces strain while enhancing the load-bearing capacity of cortical and cancellous bone. Consequently, the progressive increase in orthotropic stiffness from V1 to V7 produced substantial reductions in cortical and cancellous bone strain, whereas stress distribution remained largely unchanged. This finding indicates that orthotropic stiffness primarily influences deformation-related responses rather than altering the overall load-transfer mechanism within the implant–bone complex.

The larger strain response observed in bone compared with the metallic implant components can also be attributed to the considerable difference in elastic modulus between Ti-6Al-4V and mandibular bone. Because the implant possesses substantially higher stiffness, most deformation occurs within the surrounding bone tissue, making cortical and cancellous bone considerably more responsive to changes in orthotropic properties.

The greater sensitivity of strain relative to stress can be further explained by the load-transfer mechanism within the implant–bone complex. Under identical loading and boundary conditions, the overall force equilibrium of the system remains essentially unchanged, resulting in only minor variations in stress distribution despite changes in orthotropic material properties. In contrast, strain is governed by the local elastic compliance of the surrounding bone. Therefore, reductions in orthotropic stiffness increase local deformation while preserving the primary load-transfer pathway between the implant and supporting bone. This biomechanical response explains why cortical and cancellous bone strains exhibited substantially greater sensitivity than stress under systematic variations in orthotropic properties. From a biological perspective, excessive peri-implant strain has been associated with bone microdamage, remodeling, and marginal bone loss. Consequently, strain-based assessment may provide a more clinically relevant indicator of peri-implant biomechanical behavior than stress alone, particularly in patients presenting with reduced bone quality or compromised bone stiffness. These observations agree with (Yang et al., 2023), who reported that reduced bone quality increased peri-implant strain and that greater bone stiffness effectively minimized deformation and improved implant stability.

Clinically, these findings indicate that strain-based evaluation may provide a more sensitive indicator for assessing peri-implant biomechanical conditions, particularly in patients presenting with reduced bone quality or advanced alveolar bone resorption.

Table 7. Strain Distribution and Effect of Orthotropic Property Variations

Variation	εF (-)	εS (-)	εU (-)	εA (-)	εCt (-)	εCn (-)
V1	9.15×10^{-5}	4.36×10^{-4}	1.63×10^{-4}	4.04×10^{-4}	2.91×10^{-4}	7.43×10^{-4}
V2	9.13×10^{-5}	4.36×10^{-4}	1.63×10^{-4}	4.05×10^{-4}	2.74×10^{-4}	7.01×10^{-4}
V3	9.12×10^{-5}	4.36×10^{-4}	1.62×10^{-4}	4.06×10^{-4}	2.59×10^{-4}	6.64×10^{-4}
V4	9.68×10^{-5}	4.64×10^{-4}	1.71×10^{-4}	4.25×10^{-4}	2.44×10^{-4}	6.30×10^{-4}
V5	9.08×10^{-5}	4.35×10^{-4}	1.62×10^{-4}	4.09×10^{-4}	2.34×10^{-4}	5.99×10^{-4}
V6	9.06×10^{-5}	4.35×10^{-4}	1.62×10^{-4}	4.10×10^{-4}	2.22×10^{-4}	5.71×10^{-4}
V7	9.04×10^{-5}	4.35×10^{-4}	1.62×10^{-4}	4.11×10^{-4}	2.12×10^{-4}	5.45×10^{-4}
V8	9.06×10^{-5}	4.35×10^{-4}	1.62×10^{-4}	4.09×10^{-4}	2.33×10^{-4}	5.86×10^{-4}
V9	9.10×10^{-5}	4.35×10^{-4}	1.62×10^{-4}	4.08×10^{-4}	2.35×10^{-4}	6.15×10^{-4}

3.4 Influence of Orthotropic Properties on Displacement Behavior

Displacement exhibited an inverse relationship with orthotropic stiffness. From V1 to V7, fixture displacement decreased from 7.59 µm to 5.62 µm, corresponding to a reduction of approximately 26.0%. Similar reductions were observed in cortical bone (7.61–5.64 µm; 25.9%) and cancellous bone (7.54–5.59 µm; 25.9%). The coefficient of variation ranged from 9.70% to 9.82%, indicating that displacement responses were more sensitive than stress but less sensitive than bone strain. These findings demonstrate that increasing bone stiffness primarily reduced structural deformation while preserving the overall load-transfer characteristics of the implant system.

Table 8. Influence of Orthotropic Variations on Displacement Distribution

Variasi	δF (µm)	δS (µm)	δU (µm)	δA (µm)	δCt (µm)	δCn (µm)
1	7.59	7.41	7.40	7.63	7.61	7.54
2	7.17	7.01	7.00	7.21	7.19	7.13
3	6.80	6.65	6.64	6.84	6.82	6.76
4	6.48	6.34	6.34	6.52	6.50	6.44
5	6.15	6.02	6.02	6.19	6.17	6.12
6	5.88	5.75	5.75	5.92	5.90	5.84
7	5.62	5.51	5.51	5.66	5.64	5.59
8	6.25	6.11	6.11	6.29	6.27	6.21
9	6.09	5.96	5.95	6.13	6.11	6.05

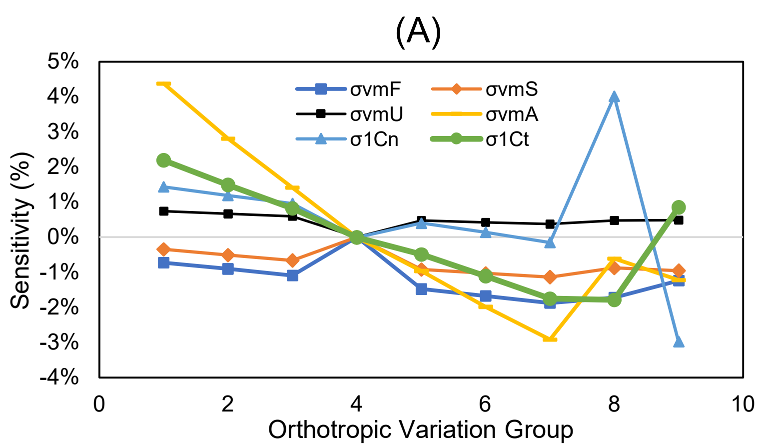
The parameter-isolation study showed that variations in Young's modulus (*V8*) generated slightly greater displacement responses than equivalent variations in shear modulus (*V9*), highlighting the stronger influence of elastic stiffness on deformation characteristics. Despite this trend, the effects associated with each isolated parameter remained modest relative to those produced by the combined orthotropic cases (*V1–V7*). These results indicate that the biomechanical response is determined by the integrated orthotropic stiffness framework, rather than being controlled by an individual material property.

Increasing orthotropic stiffness reduced displacement because a stiffer material exhibits greater resistance to elastic deformation under identical loading conditions. As the elastic modulus increases, the structural compliance of the implant–bone complex decreases, resulting in smaller overall displacement. This behaviour is consistent with classical linear elasticity theory, where structural displacement is inversely proportional to material stiffness for a constant external load. These findings are consistent with (Kriswanto, Jamari, Bayuseno, et al., 2025) demonstrated that variations in implant material properties significantly affected displacement behavior, with stiffer material configurations exhibiting lower deformation under mechanical and thermal loading conditions. Likewise, the present study shows that increasing orthotropic stiffness reduces displacement throughout both implant components and surrounding bone tissues, confirming that enhanced stiffness improves load-transfer efficiency and limits structural deformation. Furthermore, (Yang et al., 2023) reported that improvements in bone mechanical properties and implant stability reduced peri-implant strain and micromotion, supporting the present observation that stiffer orthotropic bone provides greater resistance to displacement. Overall, the relatively small displacement variations observed across all models indicate that the three-implant configuration maintains favorable biomechanical stability despite changes in orthotropic material properties.

3.5 Sensitivity of Young's Modulus and Shear Modulus

The sensitivity analysis revealed that the biomechanical response of the implant–bone system was not equally affected by variations in orthotropic material properties (Figure 6). Principal strain demonstrated the greatest sensitivity to changes in material stiffness, particularly within cortical and cancellous bone tissues. In contrast, stress distribution was only marginally affected across the orthotropic conditions evaluated. Displacement showed an intermediate response, characterized by a gradual reduction with increasing stiffness. Collectively, these findings indicate that orthotropic material behavior mainly governs the deformation characteristics of the implant–bone complex, whereas its impact on the global stress transfer mechanism remains limited.

The magnitude of sensitivity differed considerably among biomechanical parameters. Stress responses generally varied by less than 4% from the baseline condition, whereas cortical and cancellous bone strains exhibited sensitivity values approaching ±20% under the most extreme orthotropic variations. Similarly, displacement responses varied by approximately ±17%. These findings confirm that deformation-related parameters are substantially more sensitive to changes in orthotropic stiffness than stress-based parameters.



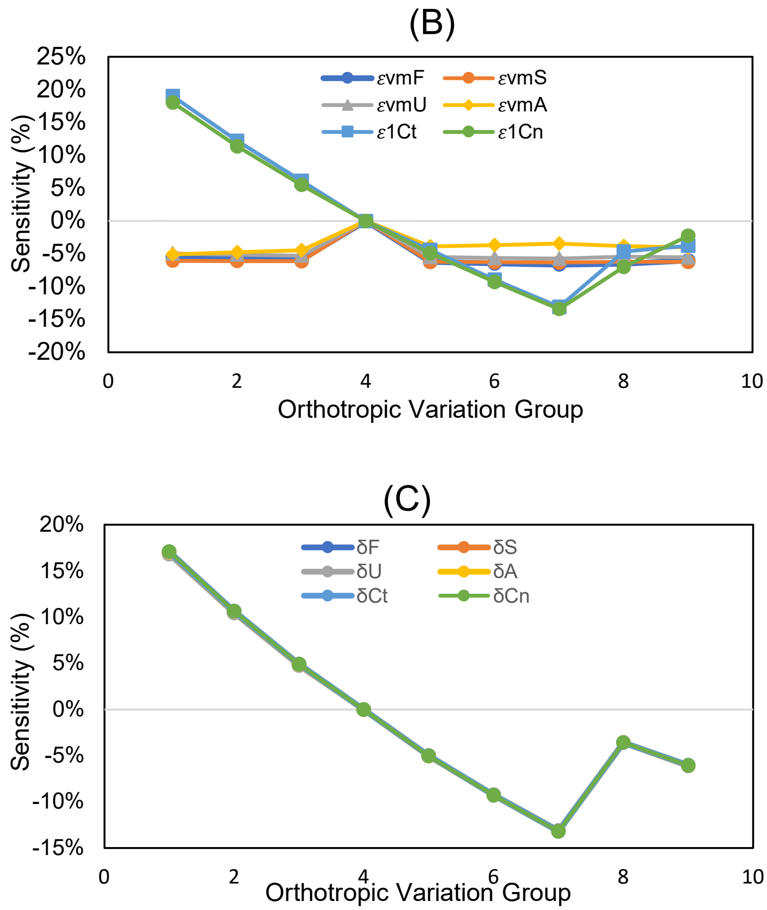


Figure 6. Sensitivity analysis of biomechanical responses to variations in orthotropic material properties: (a) stress response, (b) strain response, and (c) displacement response.

A comparison of the Young's modulus sensitivity model ($V8$) and the shear modulus sensitivity model ($V9$) revealed that changes in Young's modulus resulted in substantially greater variations in both strain and displacement than comparable alterations in shear modulus. These findings indicate that axial and directional stiffness exert a stronger influence on load transfer and overall structural deformation than shear-related properties. From a mechanical perspective, a higher Young's modulus increases the stiffness of both cortical and cancellous bone, which reduces localized deformation and minimizes implant micromotion. By comparison, modifications in shear modulus produced relatively limited effects on the biomechanical response, suggesting that its contribution to the behavior of the overall system is less pronounced.

The observed dominance of Young's modulus over shear modulus is mechanically reasonable because axial elastic stiffness directly controls the strain generated under compressive loading. Under the applied vertical load, the implant–bone system is predominantly subjected to normal stresses rather than shear stresses. Consequently, modifications in Young's modulus have a greater influence on deformation behavior, whereas changes in shear modulus contribute only marginally to the overall biomechanical response.

The present findings align with the finite element study conducted by (Yang et al., 2023), which demonstrated that peri-implant strain distribution is strongly affected by bone anisotropy, bone quality, and the degree of osseointegration. However, stress concentrations were consistently confined to the implant neck region regardless of variations in these parameters. Their results further indicated that greater bone stiffness and enhanced osseointegration decreased strain within the cancellous bone and improved overall implant stability. This suggests that strain is a more sensitive biomechanical measure than stress for detecting changes in the mechanical behavior of peri-implant bone. Similarly, the systematic review by (Kriswanto, Jamari, Andika, et al., 2025), identified bone quality and assumptions regarding material properties as key determinants of biomechanical outcomes in finite element analyses of dental implants. The authors also highlighted that simplified representations of bone material behavior can substantially influence strain estimations, whereas their effects on stress distribution are generally less pronounced.

The findings highlight Young's modulus as the dominant orthotropic parameter governing the biomechanical response of the implant–bone system. Although stress patterns exhibited minimal variation across the different material conditions, the greater sensitivity of strain and displacement responses suggests that patient-specific bone stiffness may play an important role in determining implant stability and peri-implant tissue mechanics. Nevertheless, the persistence of similar biomechanical response patterns under all orthotropic conditions supports the mechanical robustness and reliability of the three-implant design examined in this study.

From a clinical perspective, the present findings suggest that strain-based evaluation may provide a more representative indicator of peri-implant biomechanical conditions than stress-based assessment alone. Since cortical and cancellous bone strains were highly sensitive to orthotropic property variations, patient-specific bone stiffness should be considered during implant treatment planning, particularly in individuals with reduced bone quality or advanced alveolar bone resorption. Incorporating orthotropic material behavior into finite element simulations may improve the prediction of implant stability and contribute to more clinically realistic rehabilitation strategies.

3.6 Biomechanical Stability of the Three-Implant Configuration

As presented in Table 9, the coefficient of variation (CV) analysis revealed that the biomechanical behavior of the implant–bone system remained generally consistent across the different orthotropic material configurations evaluated. Among the assessed parameters, stress exhibited the lowest degree of variation, with coefficients ranging from 0.21% to 2.35%, indicating a highly stable response to changes in orthotropic material properties. In contrast, cortical and cancellous bone strains exhibited the highest variability, with CV values of 10.30% and 10.19%, respectively, while displacement responses showed intermediate variability ranging from 9.70% to 9.82%. Based on the robustness classification criteria (CV < 5% = highly robust, 5–10% = robust, and >10% = moderately sensitive), stress-related parameters were classified as highly robust, displacement responses as robust, and bone strain responses as moderately sensitive.

Table 9. Coefficient of Variation (CV) of Biomechanical Parameters Across Orthotropic Variations

Coefficient of Variation (%)		
Response Category	**Parameter**	**CV (%)**
Stress	σvmF	0.60%
	σvmS	0.37%
	σvmU	0.21%
	σvmA	2.35%
	σ1Cn	1.82%
	σ1Ct	1.42%
Strain	εvmF	2.19%
	εvmS	2.19%
	εvmU	1.91%
	εvmA	1.53%
	ε1Ct	10.30%
	ε1Cn	10.19%
Displacement	δF	9.81%
	δS	9.73%
	δU	9.70%
	δA	9.78%
	δCt	9.80%
	δCn	9.82%

These findings demonstrate that strain is the most responsive biomechanical indicator to orthotropic property variations and therefore provides greater sensitivity for detecting changes in peri-implant biomechanical behavior. The greater sensitivity of strain can be attributed to its direct dependence on material stiffness, whereas stress distribution is primarily governed by load equilibrium and geometric constraints within the implant–bone system. Despite the observed differences in parameter sensitivity, the predominance of highly robust and robust responses across most evaluated variables confirms the overall biomechanical stability and favorable load-sharing capability of the three-implant mandibular rehabilitation system within the investigated physiological range.

3.7 Clinical Implications

The present findings demonstrate that strain-based biomechanical parameters are substantially more sensitive than stress-based parameters in detecting the effects of variations in orthotropic bone properties. This observation suggests that principal strain may serve as a more reliable biomechanical indicator for evaluating peri-implant mechanical conditions, particularly in patients with heterogeneous bone quality. Since cortical and cancellous bone strain exhibited the greatest sensitivity to changes in orthotropic stiffness, incorporating patient-specific bone mechanical properties into finite element models may improve the accuracy of biomechanical predictions compared with conventional isotropic assumptions.

From a clinical perspective, these findings indicate that assessment of bone stiffness should be considered during implant treatment planning, especially in patients presenting with compromised bone quality, age-related bone loss, osteoporosis, or advanced alveolar ridge resorption. In such clinical conditions, the increased sensitivity of strain to bone mechanical properties suggests that patient-specific biomechanical evaluation may provide a more realistic estimation of peri-implant tissue loading and implant stability than stress analysis alone.

Furthermore, the observed biomechanical robustness of the three-implant mandibular rehabilitation model, characterized by relatively stable stress transfer despite systematic variations in orthotropic material properties, supports the mechanical reliability of this rehabilitation concept (Kriswanto, Jamari, Andika, et al., 2025). This robustness suggests that the three-implant configuration is capable of maintaining a consistent load-transfer mechanism even when physiological variations in bone stiffness are present. Consequently, incorporating orthotropic material behavior into computational simulations may improve the biomechanical realism of implant treatment planning and facilitate the development of more representative patient-specific finite element models for implant rehabilitation.

3.8 Study Limitations and Future Perspectives

Several limitations of this study should be acknowledged. First, the bone model was represented by a simplified bone block, which does not accurately capture the complex anatomical characteristics of an individual patient's mandible. Recent evidence suggests that patient-specific models incorporating heterogeneous material properties provide more reliable biomechanical predictions than homogeneous models or geometrically simplified representations (Soodmand et al., 2024). Second, the simulations assumed complete osseointegration by defining a fully bonded implant–bone interface. In clinical practice, however, the degree of osseointegration may vary depending on bone quality and patient-related biological factors, potentially resulting in biomechanical behavior that differs from the idealized conditions modeled in this investigation. Third, the loading protocol was limited to a static axial force of 100 N. Under physiological conditions, the stomatognathic system is subjected to dynamic and multidirectional forces, including axial, lateral, and oblique components during mastication. Consequently, the simplified loading scenario employed in this study may not fully represent the complex mechanical environment experienced in vivo. Recent studies have therefore emphasized the importance of incorporating multiscale modeling approaches and more clinically relevant loading conditions to enhance the predictive accuracy of finite element analyses in implant dentistry (Falcinelli et al., 2023).

Future studies should incorporate patient-specific mandibular anatomies reconstructed from three-dimensional imaging data, as well as heterogeneous material properties obtained from radiographic assessments. Consideration should also be given to varying degrees of osseointegration and dynamic loading scenarios that more accurately reflect physiological masticatory function. Furthermore, experimental investigations and clinical validation are essential to verify the biomechanical significance of bone remodeling simulations and to establish their applicability to real-world clinical settings.

CONCLUSIONS

Based on the FEA findings, this study presents the following conclusions:

1. This study successfully developed and verified a three-dimensional finite element model incorporating orthotropic cortical and cancellous bone properties to evaluate the biomechanical sensitivity of a three-implant mandibular rehabilitation system. Mesh convergence analysis confirmed numerical stability and demonstrated that the model was suitable for orthotropic material-sensitivity assessment.
2. Variations in orthotropic bone properties influenced all evaluated biomechanical responses, including stress, principal strain, and displacement. Increasing Young's modulus and shear modulus generally reduced stress concentration, strain magnitude, and structural deformation, indicating that bone stiffness plays a critical role in load transfer within the implant–bone complex.
3. Principal strain exhibited the highest sensitivity to orthotropic material variations, particularly in cortical and cancellous bone, with coefficients of variation of 10.30% and 10.19%, respectively. In contrast, stress responses remained highly stable, with CV values below 2.35%, indicating that strain is a

more sensitive biomechanical indicator of changes in bone mechanical properties than stress.

4. Sensitivity analysis demonstrated that Young's modulus exerted a greater influence than shear modulus on the biomechanical behavior of the implant–bone system, particularly with respect to strain and displacement responses. These findings highlight elastic stiffness as the dominant orthotropic parameter governing peri-implant deformation and overall structural stability
5. Despite variations in orthotropic material properties, the three-implant mandibular prosthesis configuration maintained a consistent biomechanical response pattern, with displacement CV values ranging from 9.70% to 9.82% and stress CV values below 2.35%, indicating favorable biomechanical robustness and load-sharing capability. Clinically, these findings suggest that patient-specific orthotropic bone properties should be considered during implant treatment planning and biomechanical simulation, as strain-based metrics may provide a more reliable basis for evaluating implant placement strategies, predicting peri-implant tissue behavior, and developing clinically representative finite element models.

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