

## **Parametric Optimization and Analysis of Orthodontic Mini Screws Using Finite Element Analysis (FEA)**

Mr. Subodh Chavan<sup>1</sup>, Mr. Pritish Chitte<sup>2\*</sup>, Dr. Bhagyesh Deshmukh<sup>3</sup>, Dr. Vivek Chitte<sup>4</sup>

<sup>1</sup>*Research Scholar, Department of Mechanical Engineering, Walchand Institute of Technology, Solapur, India*

<sup>2</sup>*Assistant Professor, Department of Mechanical Engineering, Walchand Institute of Technology, Solapur, India*

<sup>3</sup>*Professor, Department of Mechanical Engineering, Walchand Institute of Technology, Solapur, India*

<sup>4</sup>*Reader, Department of Orthodontics, S. B. Patil Dental College and Hospital, Bidar, India*

### **Abstract**

*Orthodontic mini screws, widely used as temporary anchorage devices, require optimal biomechanical performance to ensure clinical stability and long-term success. The present study aims to develop and evaluate an optimized design of orthodontic mini screws through parametric analysis and finite element analysis (FEA). Critical design and material parameters, including thread geometry, screw diameter, material selection, and insertion characteristics, were systematically investigated to assess their influence on primary stability, stress distribution, and retention behavior. Linear static finite element simulations were carried out on both initial and optimized mini screw models fabricated from stainless steel 316L and titanium alloy Ti-6Al-4V. The optimized design exhibited a notable reduction in von Mises stress, total deformation, and contact pressure at the bone-implant interface when compared with the initial configuration. Design modifications also addressed common clinical challenges such as high insertion resistance, early loosening, and the risk of premature failure under orthodontic loading conditions. The results demonstrate that geometric optimization, independent of material change, significantly enhances biomechanical efficiency and anchorage reliability. The outcomes of this study provide valuable insights for the development of safer, more stable, and clinically predictable orthodontic mini screws, supporting improved treatment outcomes and future design innovations.*

Keywords: Orthodontic mini screw, Design optimization, Finite element analysis, Titanium alloy, Stainless steel

## 1. Introduction

Orthodontic mini screws, commonly referred to as Temporary Anchorage Devices (TADs), have significantly advanced orthodontic treatment by offering stable, efficient, and compliance-independent anchorage for controlled tooth movement. Mini screws are small, screw-like devices made primarily of stainless steel or titanium alloys due to their excellent biocompatibility, corrosion resistance, and mechanical strength. Typically ranging from 6 mm to 12 mm in length and 1 mm to 2 mm in diameter, but majorly 1.6 mm diameter screws proffered length of screw can be vary that depends on bone structure of patient. Poorly optimized design may lead to early failure that's why optimized design is necessary. The performance and clinical success of mini screws are highly sensitive to geometric and mechanical design parameters including thread pitch, screw diameter, length, head and hexagonal nut height, insertion angle, and surface roughness. These features influence not only the mechanical retention in bone but also the biological response from surrounding soft and hard tissues. Special attention is given to design optimization methods using computational tools such as finite element analysis, as well as biological studies focusing on soft tissue compatibility, and long-term stability. By integrating insights from both engineering and biomedical domains, this research contributes a multi-disciplinary perspective aimed at enhancing the clinical utility, safety, and effectiveness of orthodontic mini screws. Over the past two decades, researchers have investigated different screw designs, thread modifications, and surface treatments to enhance primary and secondary stability. While these studies have provided valuable insights, there remains a gap in integrating computational simulations with experimental validations and clinical considerations. Furthermore, most available data are based on single-center or small-sample studies, which limit general liability. Longitudinal, multicenter investigations are required to fully establish evidence-based design guidelines for orthodontic mini screws.

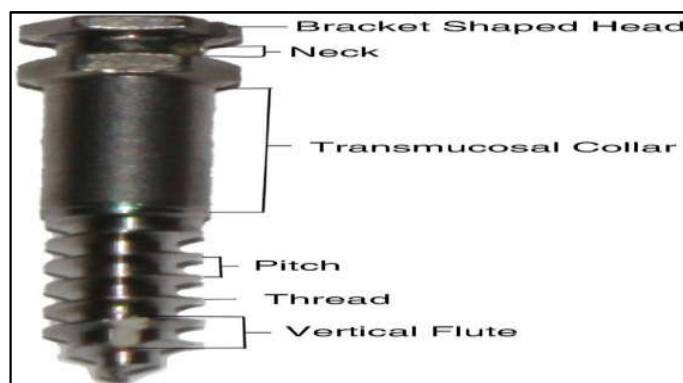


Fig1: Orthodontic mini screw

Orthodontic mini screws are critical for achieving absolute anchorage, with their clinical success hinging on the design of six major components. The threaded portion and its pitch are vital for primary stability; the threads mechanically interlock with the cortical bone, while a smaller pitch increases bone contact and improves stability. The vertical flute enhances the self-drilling capability by cutting bone and removing debris, minimizing insertion trauma. The transmucosal collar is a smooth neck that ensures proper clearance between the bone, featuring a polished surface to reduce plaque and soft tissue irritation. The neck connects the threaded body to the head, providing mechanical strength and stress distribution. Finally, the

versatile bracket-shaped head serves as the crucial attachment interface for orthodontic auxiliaries (elastics, springs, wires), allowing for flexible application of orthodontic forces.

Previous studies have primarily focused on isolated parameters such as material selection, insertion angle, or surface treatment of orthodontic mini screws. However, limited research has addressed comprehensive geometric optimization using finite element analysis while maintaining consistent material properties and clinically relevant loading conditions. Moreover, the combined effect of thread geometry modification and stress redistribution at the bone-implant interface remains insufficiently explored. The present study addresses this gap by performing a systematic parametric redesign of orthodontic mini screws and evaluating their biomechanical performance through finite element analysis, thereby providing design-driven insights for improving primary stability and clinical reliability.

## 2. Materials and Methods

The research methodology consists of three major stages: material selection, three-dimensional computer-aided design (CAD) modeling, and finite element analysis. Two commonly used biomaterials, stainless steel 316L and titanium alloy Ti-6Al-4V, were selected due to their proven biocompatibility and mechanical performance in dental applications. CAD models of both initial and optimized orthodontic mini screws were developed using Autodesk Fusion 360 software. Linear static finite element analysis was conducted to evaluate von Mises stress, total deformation, contact pressure, and safety factor under orthodontic loading conditions.

### 2.1 Materials considered for manufacturing of orthodontic mini screw

**Stainless steel 316L:** (low-carbon austenitic stainless steel) is widely used in biomedical and dental applications due to its excellent mechanical strength, corrosion resistance, and biocompatibility. The “L” stands for low carbon minimizes carbide precipitation during fabrication and sterilization and helps in improving its resistance to corrosion. Stainless steel 316L has high tensile and yield strength ensures resistance at the time of loading. It has good ductility and toughness allows good machining and threads. And it has excellent corrosion resistance in oral cavity environment and one more advantage of this material is its cost effectiveness.

**Titanium alloy Ti-6Al-4V:** Titanium alloy Ti-6Al-4V, composed of approximately 90% titanium, 6% aluminum, and 4% vanadium, is one of the most widely used biomaterials in dental and orthodontic implants. It has superior combination of mechanical strength, low density, and exceptional biocompatibility. This material has high strength to weight ratio and outstanding corrosion resistance. It also has excellent biocompatibility results in better tissue response and minimizes allergic reactions.

**2.2 Finite Element Model Description:** A three-dimensional finite element model of the orthodontic mini screw and surrounding bone block was developed to evaluate biomechanical behavior under orthodontic loading. The bone block was modeled as a two-layer structure consisting of cortical and cancellous bone to represent anatomical conditions. The bone block has rectangular in dimension of 20\*20\*2 (W\*D\*H) for cortical bone and 20\*20\*13 (W\*D\*H) for cancellous bone and mini screw based in middle of bone block with angle of 90 degree and then performed linear static analysis with applied load of 2N vertically on head of orthodontic mini screws and fixed base block base. The dimensions of the cortical and

cancellous bone blocks were selected to minimize boundary effects while ensuring sufficient surrounding bone volume for realistic stress distribution. These dimensions are consistent with commonly adopted finite element modeling approaches for orthodontic mini screw analysis reported in the literature

## 2.2 3D CAD Model and FEA analysis of INITIAL orthodontic mini screw

### 2.2.1 Computer aided Drafting of INITIAL orthodontic mini screw

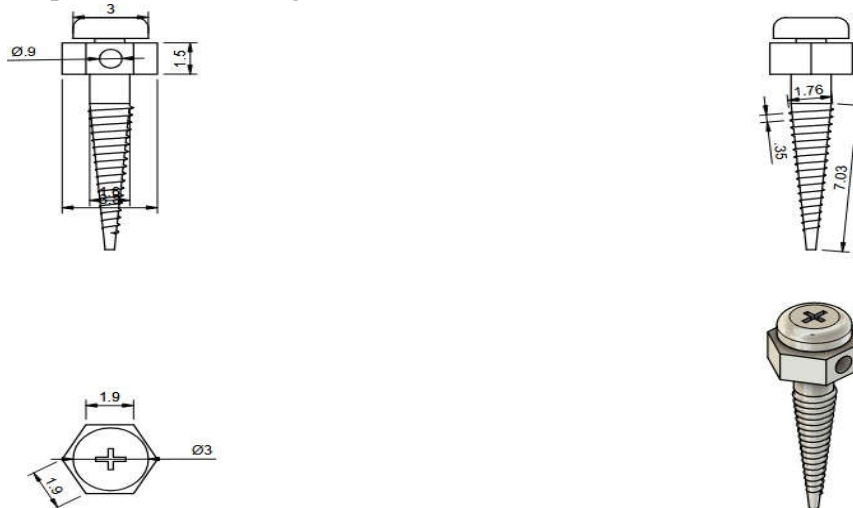


Fig2: Computer aided Drafting of initial orthodontic mini screw

### 2.2.2 FEA Linear Static Analysis of INITIAL Orthodontic Mini screw (Stainless steel 316L)

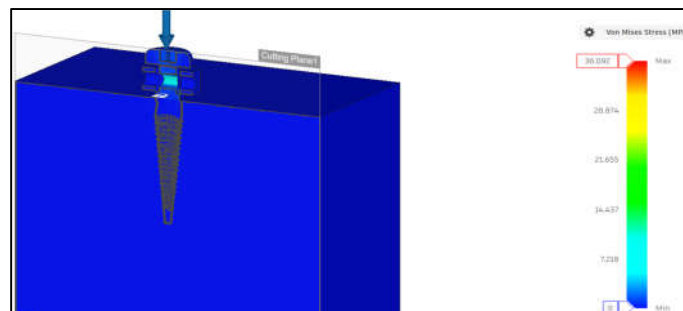


Fig 3: Von mises stresses



Fig 4: Deformation

**2.2.3 FEA Linear Static Analysis of INITIAL Orthodontic Mini screw (Titanium Ti-6Al-4V alloy):**

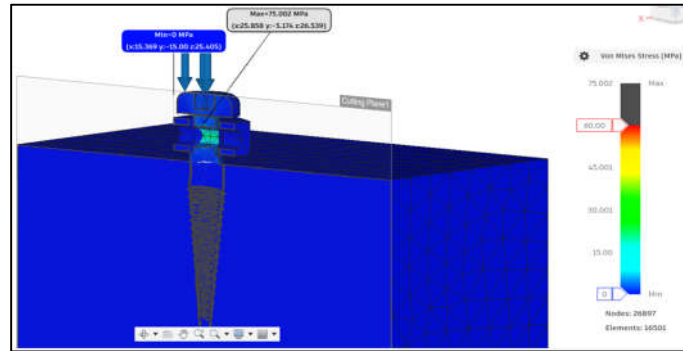


Fig 5: Von mises stresses

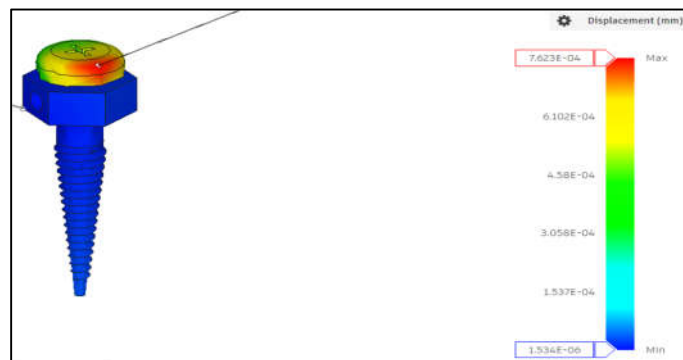


Fig 6: Deformation

**2.2.3 Finite Element Analysis (FEA) Linear Structural analysis Results and Analysis:**

**Table1:** Comparison of FEA analysis of INITIAL orthodontic mini screw

Parameter	Initial screw (SS316L)	Initial screw (Ti-6Al-4V)
Material	Stainless steel 316L	Titanium alloy (Ti-6Al-4V)
Von-mises stresses	36.092 Mpa	75.002 Mpa
Deformation	1.95 mm	7.623 mm

The comparative finite element analysis results in such a way that the orthodontic mini screw of material titanium alloy Ti-6Al-4V outperforms the stainless steel 316L screw with respect to stress distribution, contact pressure, and likely safety factor. The titanium alloy made orthodontic screw reduces peak stresses and distributes loads more evenly along the bone implant interface, which can enhance primary stability, decrease the likelihood of micro-fracture in cortical bone, and improve long term clinical performance.

### 2.3 3D CAD Model and FEA analysis of OPTIMIZED orthodontic mini screw

The optimized orthodontic mini screw design was developed based on biomechanical considerations aimed at improving primary stability, reducing stress concentration, and minimizing insertion-related complications observed in the initial design. Key geometric modifications included refinement of the thread profile, adjustment of core diameter, optimization of thread pitch, and smoothing of stress transition regions between the threaded body, neck, and head. These changes were introduced to enhance load transfer efficiency from the screw to the surrounding bone and to reduce localized stress peaks that may contribute to early loosening or mechanical failure. The threads are designed manually and thread angles and increased while considering solving the problems of early loosening and failure at the threaded region. The important thing is here tip of the orthodontic mini screw is designed in such a way that it does not break at the time of insertion he optimized tip geometry was reinforced through localized geometric modification to improve mechanical strength during insertion and to reduce the risk of tip fracture under insertion. The objective of the present study was comparative biomechanical evaluation using finite element analysis rather than analytical derivation. Therefore, geometric modifications such as thread angle variation were justified based on numerical simulation results and established biomechanical principles, consistent with prior FEA-based orthodontic implant studies.

#### 2.3.1 Computer aided Drafting of OPTIMIZED orthodontic mini screw

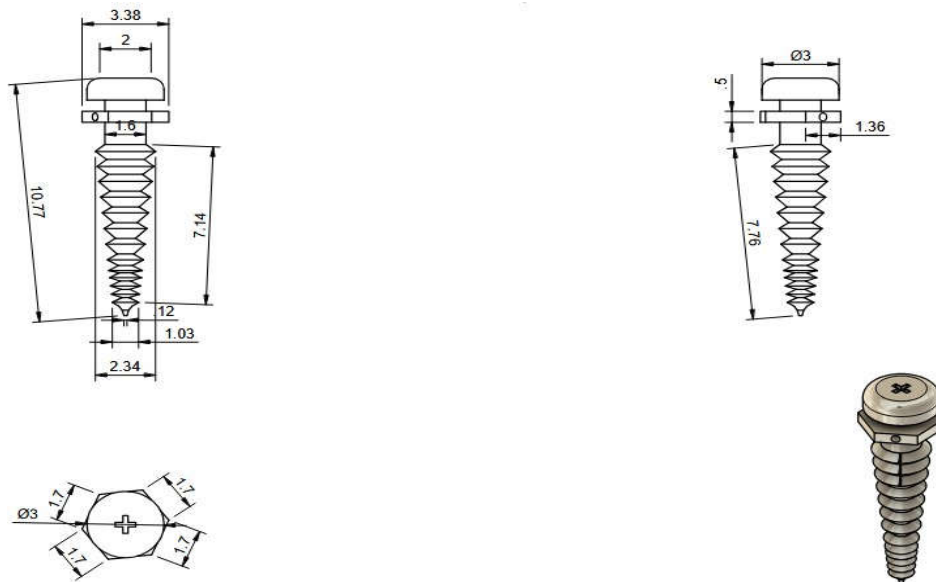


Fig 7: Computer-aided drafting of the optimized orthodontic mini screw showing modified thread geometry, reinforced tip region, and smoother head–neck transition.

**2.3.2 FEA Linear Static Analysis of OPTIMIZED Orthodontic Mini screw (Stainless steel 316L)**



Fig 8: Von mises stresses

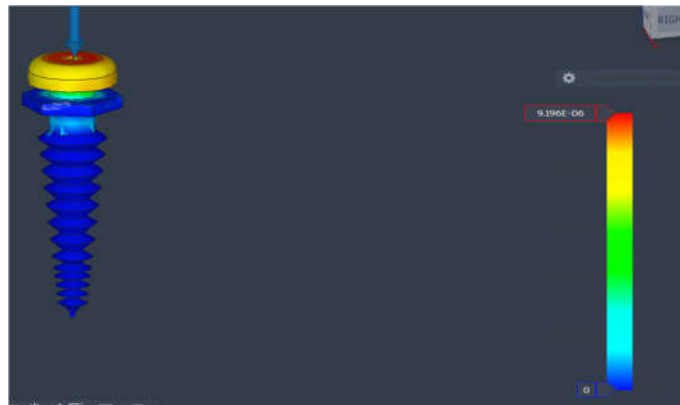


Fig 9: Deformation

**2.3.3 FEA Linear Static Analysis of OPTIMIZED Orthodontic Mini screw (Titanium Ti-6Al-4V alloy):**

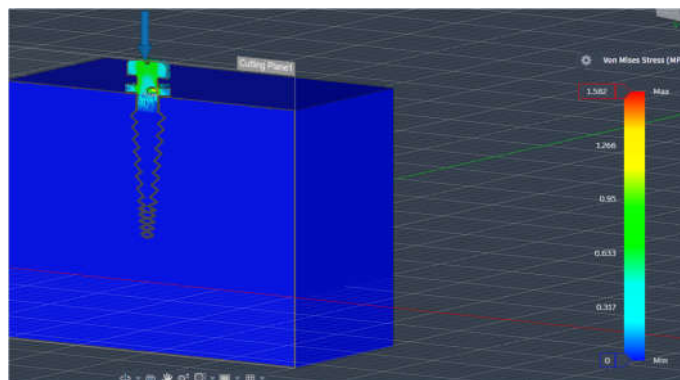


Fig 10: Von mises stresses



Fig 11: Deformation

**2.3.4 Finite Element Analysis (FEA) Linear Structural analysis Results and Analysis:**  
**Table2:** Comparison of FEA analysis of OPTIMIZED orthodontic mini screw

Parameter	Optimized screw (SS316L)	Optimized screw (Ti-6Al-4V)
Material	Stainless steel 316L	Titanium alloy (Ti-6Al-4V)
Von-mises stresses	1.669 Mpa	1.582 Mpa
Deformation	9.196 mm	1.417 mm

The optimized stainless-steel model made of stainless steel 316L exhibits extremely high young's modulus compared to titanium screw, this results in optimized screw of stainless-steel model being stiffer and experiencing less maximum total deformation under the same load crucial findings for application requiring high dimensional stability. Both materials made of design meet the minimum requirement of safety factor greater than 1.

### 3. Finite Element Analysis (FEA) and interpretation of original and optimized orthodontic screws:

**Table 3:** Comparison of FEA analysis of ORIGINAL and OPTIMIZED orthodontic mini screw

Parameter	Initial screw (SS316L)	Initial screw (Ti-6Al-4V)	Optimized screw (SS316L)	Optimized screw (Ti-6Al-4V)
Max-von mises stresses	36.092 Mpa	75.002 Mpa	1.669 Mpa	1.582 Mpa
Total deformation	1.95 mm	7.623 mm	9.196 mm	1.417 mm
Safety factor	4.721	11.828	15	15
Max contact pressure	6.803 Mpa	14.371 Mpa	0.772 Mpa	0.777 Mpa
Maxcontact force	0.568 N	1.133 N	0 N	0 N

### 4. Results and Discussions

- 1. Stress distribution:** The optimized mini screws give significant reduction in max von mises stresses when compared to initial models. The optimized models of both the materials exhibited stresses approximately 1.6Mpa which is better than comparison of initial mini screw exhibits around 6. 803Mpa.The significant reduction in von Mises stress observed in the optimized orthodontic mini screw models can be attributed to the improved geometric configuration, including modifications in thread profile, core diameter, and load transfer pathway. These design changes enabled a more uniform distribution of stresses along the bone-implant interface, thereby minimizing localized stress concentrations commonly associated with early loosening or failure of mini screws. Importantly, the observed stress reduction occurred independent of material selection, indicating that geometric optimization plays a dominant role in enhancing biomechanical performance.”
- 2. Total deformation:** All models give the deformation results in range of 1.417 to 9.196 provides excellent stiffness and rigidity of screws. The optimized 316L Design showed lower deformation values indicated better load distribution. The total deformation results obtained from the finite element analysis represent relative displacement magnitudes within the simulation environment.The apparent high deformation values are attributed to the simplified bone-implant interaction assumptions and the linear elastic material model adopted in the present study. In clinical conditions, actual displacements are significantly

lower due to bone remodeling, viscoelastic damping, and surrounding biological constraints. Therefore, deformation results are interpreted comparatively to evaluate design performance rather than as absolute clinical displacement values. Although stainless steel 316L exhibits higher stiffness due to its higher Young's modulus, the optimized titanium alloy Ti-6Al-4V model demonstrated lower total deformation under the same loading conditions. This behavior is attributed to improved load distribution and geometry-dependent flexibility of the optimized titanium design rather than material stiffness alone.

3. **Safety factor:** The safety factor of all four models is high and ranging from 4.721 to 15 the optimized design has slightly better safety factor proves that optimization did not compromise structural integrity. The safety factor values obtained for the optimized orthodontic mini screw models were observed to be significantly higher than those of the initial designs. This outcome is primarily due to the conservative loading conditions applied in the present study, where orthodontic forces were limited to physiological ranges and linear static analysis was employed. Additionally, the optimized geometry resulted in improved stress distribution and reduced stress concentration zones, thereby increasing the calculated safety factor. Although absolute safety factor values appear high, these results confirm that geometric optimization did not compromise structural integrity and instead enhanced mechanical reliability under orthodontic loading conditions. For consistency and conservative interpretation, safety factor values presented in the comparative table were limited to a capped value representing adequate structural safety under orthodontic loading conditions
4. **Contact pressure and contact force:** the optimized models show marginal reduction in both contact pressure and contact force, the maximum contact pressure decreased from 6.8 Mpa to 0.77 Mpa and contact force reduced from 0.568N to 0N. These findings suggest improved load transfer bone screw interface stability. Minimizing the risk of micro damage. The optimized orthodontic mini screw designs exhibited a marked reduction in contact pressure and contact force at the bone-implant interface. This improvement can be explained by the enhanced surface engagement and load-sharing mechanism introduced through geometric redesign. Lower contact pressure indicates improved load transfer efficiency and reduced risk of micro-damage to the surrounding cortical bone, which is clinically beneficial for maintaining primary stability and minimizing bone resorption during orthodontic treatment. In the optimized models, near-zero contact force values were observed under static loading conditions due to the idealized contact formulation and bonded interface assumptions used in the finite element model. This assumption represents perfect mechanical engagement between the mini screw and surrounding bone, which allows for efficient load transfer without relative sliding at the interface. While this represents an idealized condition, it is useful for comparative evaluation of design performance under controlled simulation conditions. The near-zero contact force observed in the optimized models results from the bonded contact assumption adopted at the bone-implant interface in the finite element model. This assumption represents ideal mechanical engagement without interfacial sliding and is commonly used in comparative FEA studies to isolate geometric effects on stress and load transfer behavior.”
5. **Clinical relevance**  
From a clinical perspective, the observed reductions in stress concentration, contact pressure, and deformation indicate enhanced primary stability and

reduced likelihood of early mini screw failure. Improved biomechanical performance is particularly beneficial during the initial healing phase, where excessive stress and micro-movement can lead to loosening. Therefore, the optimized orthodontic mini screw design offers improved predictability and reliability for anchorage applications under routine orthodontic loading conditions

The numerical results obtained in the present finite element analysis were evaluated within the context of physiological orthodontic loading conditions. The applied orthodontic force of 2 N lies within clinically accepted force ranges, ensuring realistic stress magnitudes within the mini screw. The von Mises stress values obtained for both initial and optimized designs remain significantly below the yield strength of stainless steel 316L and titanium Ti-6Al-4V alloys, confirming mechanical safety under functional loading. Although relatively high safety factor values were observed, these are attributed to conservative loading assumptions, linear elastic material modeling, and idealized bone-implant bonding conditions. Therefore, the numerical results are interpreted comparatively to assess design efficiency rather than as absolute predictors of clinical failure. The observed reductions in stress, contact pressure, and deformation after optimization demonstrate numerically realistic improvements in load transfer behavior and primary stability

The present study is limited by the use of linear static finite element analysis and simplified material and contact assumptions. Biological factors such as bone anisotropy, remodeling, and long-term cyclic loading were not considered. Future studies should incorporate nonlinear material behavior, experimental validation, and clinical investigations to further substantiate the biomechanical advantages of the optimized orthodontic mini screw design.

## 5. Conclusion

The FEA analysis results confirm that optimizes orthodontic mini screw designs significantly improve biomechanical performance over the initial models. Both 316L stainless steel and titanium Ti-6Al-4V materials showed lower stress, concentration, reduced contact pressure, and maintained stiffness. The titanium Ti-6Al-4V alloy shows superior strength to weight performance and excellent biocompatibility, while 316L stainless steel can be considered as cost-effective option with satisfied mechanical safety. Overall, the optimization improved load transfer efficiency, reduced peak stresses, and improved mechanical stability, validating the optimized designed screw as structurally and clinically more reliable alternatives for orthodontic anchorage application. For maximum structural reliability and long-term clinical predictability, the use of a high-strength Titanium Alloy remains advantageous due to its superior intrinsic mechanical properties, resulting in the highest overall safety factors. The optimized orthodontic mini screw can fix the problems that were present in initial model such as resistance at the time of insertion, early loosening etc. This confirms that geometric redesign alone significantly enhances the structural reliability and lifespan of the mini-implant.

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