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Article

Biomechanical Performance of Orthodontic Mini-Implant Materials under Different Orthodontic Loads: A Finite Element Analysis

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Abstract

Orthodontic mini-implants are widely used as temporary anchorage devices, and their biomechanical performance is influenced by implant material and applied orthodontic load. This study aimed to provide a standardized biomechanical comparison of commercially pure titanium (CP-Ti), Ti6Al4V alloy, and stainless steel 316L orthodontic mini-implants under different orthodontic loads using three-dimensional FEA. A standardized mini-implant was modelled and inserted into layered cortical-cancellous bone model. Simulations were performed in Autodesk Fusion version 2702.1.58. All materials were assumed to be homogeneous, isotropic, and linearly elastic. Lateral load of 2 N, 4 N, 6 N were applied to simulate orthodontic force. Von Mises stress, displacement, and contact pressure at the bone-implant interface were evaluated. Increasing the applied load from 2 N to 6 N produced a proportional increase in all evaluated mechanical parameters. At the maximum load of 6 N, the maximum Von Mises stress reached 38.67 MPa for CP-Ti, 37.90 MPa for Ti6Al4V, and 44.44 MPa for SS316L. The corresponding maximum displacement values were 1.5×10^{-5} mm, 1.5×10^{-5} mm, and 1.1×10^{-5} mm, respectively. Maximum contact pressure at the bone implant interface reached 55 MPa, 56 MPa and 52 MPa, respectively. Increasing orthodontic load increased stress, displacement and contact pressure regardless of the material. The results indicate that orthodontic loading magnitude has a greater influence on biomechanical response than implant material, although material properties affect stress and mechanical behavior. This study provides biomechanical evidence that may support material selection for orthodontic mini-implants and guide future experimental and clinical investigations.

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1. Introduction

Orthodontic mini-implants or temporary anchorage devices have become an important component of contemporary orthodontic treatment because they provide stable skeletal anchorage without requiring extensive patient compliance. Mini-implants offer several advantages compared with the conventional anchorage methods, including minimally invasive placement, immediate loading capability, low cost, and ease of removal after treatment completion. These characteristics have led to widespread clinical applications [1], [2], [3], [4].

The mechanical stability and long-term performance of orthodontic mini-implants remain a critical concern because of their failure. The most common failure of orthodontic mini-implant is associated with excessive stress concentration at the bone-implant interface, insufficient primary stability, poor bone quality, inappropriate loading conditions, and stress concentration at the bone-implant interface [5], [6]. The excessive stress and micromotion may induce microdamage within the surrounding cortical bone, leading to bone remodeling, implant loosening or premature failure. Therefore, understanding the biomechanical interaction between the implant and the surrounding bone is essential for improving implant stability and long-term clinical performance.

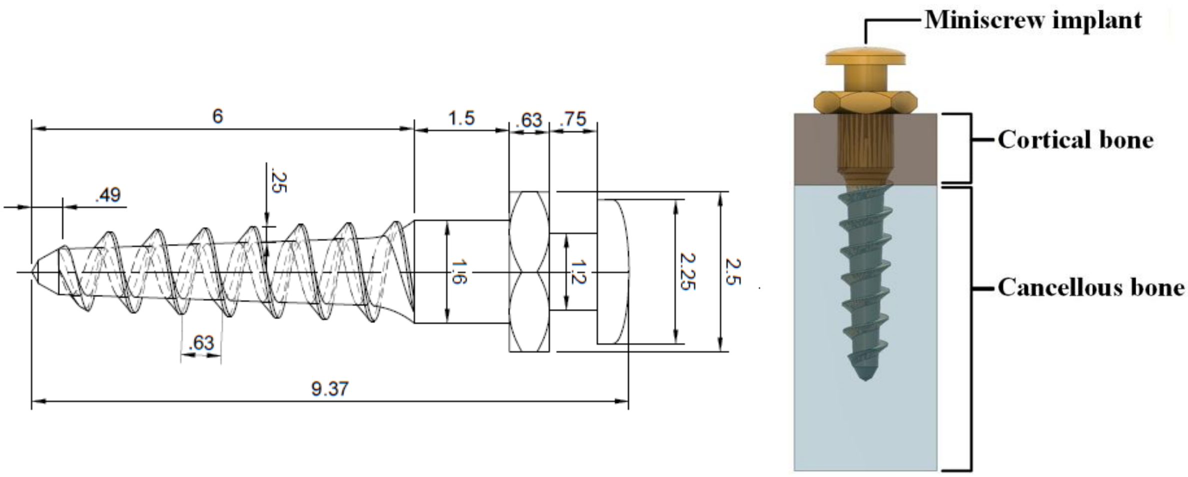
Among the factors influencing mini-implant stability, implant material properties and applied orthodontic loading play important roles. Commercially pure titanium (CP-Ti), titanium alloy Ti6Al4V, and stainless steel 316L are among the most commonly used materials in orthodontic and orthopedic implant applications due to their favorable mechanical and biocompatibility characteristics. CP-Ti is widely utilized because of its excellent corrosion resistance and high biocompatibility, although its mechanical strength is relatively lower compared with titanium alloys. Ti6Al4V exhibits a higher strength-to-weight ratio and superior fatigue resistance, making it suitable for load-bearing biomedical applications [7], [8]. Meanwhile, stainless steel 316L remains clinically relevant because of its high rigidity, ease of fabrication, and lower manufacturing cost. However, significant differences in elastic modulus, yield strength, and surface properties among CP-Ti, Ti6Al4V, and stainless steel 316L may influence stress transfer mechanisms at the bone–implant interface. Excessive mismatch between implant stiffness and bone mechanical properties can increase stress shielding effects and potentially alter bone remodeling behavior surrounding the implant [5], [6].

The mechanical response of orthodontic mini-implants is also strongly influenced by the magnitude of the applied orthodontic load. In clinical practice, orthodontic forces are generally maintained within a controlled range to achieve effective tooth movement while minimizing adverse mechanical effects on the implant and surrounding bone. Previous experimental and computational studies have demonstrated that increasing orthodontic load produces higher stress concentration, strain, and displacement, particularly around the implant neck where cortical bone experiences the greatest mechanical demand [9]. Although orthodontic forces between 2 and 6 N are commonly applied depending on treatment objectives, variations in load magnitude, insertion angle, and bone density may significantly influence stress distribution, implant deformation, and force transfer to the surrounding bone.

Finite element analysis (FEA) has become one of the most powerful computational techniques for evaluating the biomechanical behavior of dental and orthopedic implants. Compared with experimental testing, FEA enables non-destructive quantitative evaluation of stress distribution, strain, displacement, reaction force, and contact mechanics within complex biological structures under controlled loading conditions. Because direct measurement of stresses at the bone–implant interface is technically difficult and often impractical, finite element modelling has become an indispensable tool for investigating implant biomechanics, optimizing implant design, and evaluating the influence of material properties under simulated clinical conditions [10].

Several previous finite element studies have investigated the biomechanics of orthodontic mini-implants under different clinical conditions. Panaite et al. [8] evaluated the influence of insertion angle on stress distribution under a 2 N lateral load and reported the higher insertion angles reduced stress concentration in the cortical bone. Rahimi et al. [10] investigated the effect of cortical bone thickness and demonstrated that increasing cortical thickness significantly improves primary implant stability by reducing implant displacement. Likewise, Shinya et al. [11] analyzed the influence of thread geometry and loading direction, showing that thread design altered the stress distribution at the bone-implant interface. Although these studies [8], [10], [11] have substantially improved the understanding of orthodontic mini-implant biomechanics, they primarily focused on geometric characteristics, insertion parameters or bone morphology. In most cases, only one or two biomechanical outcomes, such as Von Mises stress or implant displacement, were reported. Furthermore, direct comparisons of commonly used implant materials under identical computational conditions remain limited. Because implant materials possess different mechanical properties, variations in stress, deformation and contact pressure at the bone implant interface may occur even when implant geometry and loading conditions are identical. A comprehensive evaluation of multiple biomechanical parameters such as Von Mises stress, strain, displacement, and contact pressure using a finite element model has received less attention.

Therefore, the present study aims to evaluate the biomechanical performance of orthodontic mini-implants manufactured from commercially pure titanium (CP-Ti), Ti6Al4V alloy, and stainless steel 316L under orthodontic loads of 2 N, 4 N, and 6 N using finite element analysis. The mechanical performance of each material is assessed by analyzing Von Mises stress, equivalent strain, displacement, reaction force, and contact pressure. The findings are expected to provide a comprehensive understanding of the influence of implant material and loading magnitude on implant biomechanics. This study provides biomechanical evidence that may support material selection for orthodontic mini-implants and guide future implant design optimization.



(a) (b)

Figure 1. Dimension of orthodontic mini-implant (a) and a finite element model of an orthodontic mini-implant inserted into alveolar bone (b).

2. Methods

A three-dimensional finite element model of an orthodontic mini-implant inserted into alveolar bone was developed using Autodesk Fusion version 2702.1.58. Figure 1 shows the implant dimensions and the finite element model of an orthodontic mini-implant used in this study. The model consisted of three main components: cortical bone, cancellous bone and orthodontic mini-implant. The cortical bone thickness and geometric dimensions were designed based on average anatomical characteristics reported in previous orthodontic biomechanics studies [12]. The orthodontic mini-implant model was designed with a cylindrical threaded geometry commonly used in clinical orthodontic anchorage systems. Three different implant materials were evaluated in this study: commercially pure titanium (CP-Ti), Ti6Al4V alloy, and stainless steel 316L.

All materials used in the finite element simulation were assumed to be homogeneous, isotropic, and linearly elastic. The mechanical properties assigned to cortical bone, cancellous bone, and implant materials were obtained from previously published literature [13], [14]. The mechanical properties used in the finite element model are presented in Table 1.

The finite element model was discretized using three-dimensional tetrahedral solid elements. Mesh convergence analysis was performed to ensure numerical accuracy and solution stability. Finer mesh refinement was applied around the bone–implant interface region because stress concentration was expected to occur near the implant threads and cortical bone contact area, in order to improve stress predictions. The final mesh consisted of 357804 nodes and 230442 elements (Figure 2).

2.1. Boundary conditions and loading

Boundary conditions were applied by fixing the outer surfaces of the alveolar bone model to restrict rigid-body motion during simulation. Orthodontic loading was applied horizontally at the head region of the mini-implant to simulate clinical orthodontic force application.

Table 1. Mechanical properties used in the finite element model.

Material	Young's Modulus (GPA)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Density (kg/mm^3)
Cancellous Bone	1.37	0.30	6	6	2.7x10^{-07}
Cortical Bone	13.7	0.30	114	133	2.0x10^{-06}
CP-Ti	115.8	0.34	139.9	213.1	4.5x10^{-06}
Ti6Al4V alloy	113.8	0.35	882.5	1034.2	4.43x10^{-06}
Stainless Steel 316L	193	0.25	170	484	7.99x10^{-06}

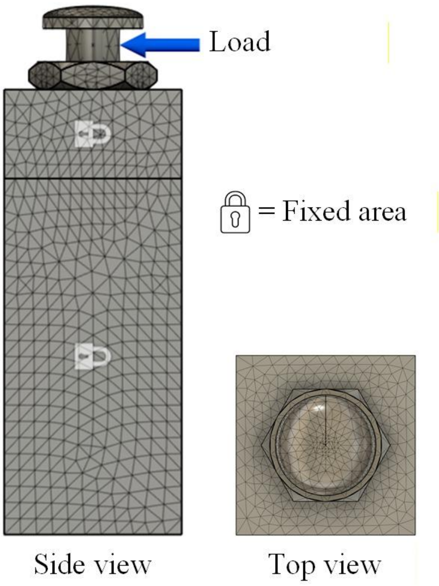


Figure 2. Finite element mesh, loading direction, and fixed boundary condition of the orthodontic mini-implant model.

Three loading magnitudes were evaluated in this study: 2 N, 4 N, and 6 N (Figure 2). These loading conditions were selected to represent common orthodontic force ranges used in clinical anchorage procedures. Separate simulations were conducted for each implant material and loading condition combination.

2.2. Contact assumptions

The contact between the mini-implant and surrounding bone was assumed to be bonded to simulate complete osseointegration conditions. This assumption was applied to simplify interface interaction and evaluate stress transfer behavior between implant materials and bone tissues.

2.3. Finite element analysis

Finite element simulations were conducted to evaluate von Mises stress distribution, displacement and contact pressure at the bone–implant interface. Stress distribution in cortical bone, cancellous bone, and implant body was analyzed for each loading condition and implant material.

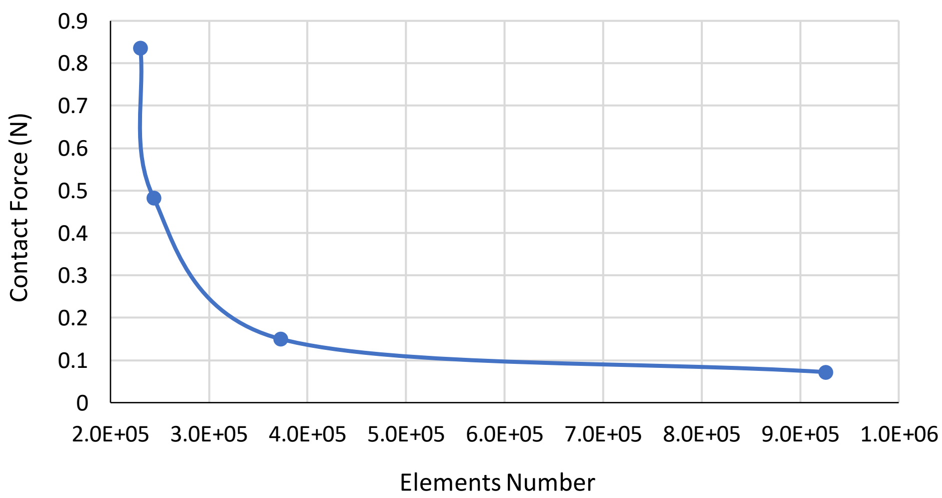


Figure 3. Mesh sensitivity analysis showing the relationship between element number and contact force (N).

The maximum von Mises stress and displacement values were recorded and compared to determine the influence of implant material and loading magnitude on mechanical stability. Contact pressure showed the pressure acting between the orthodontic mini-implant and the cortical bone.

2.4. Model validation

The finite element model was evaluated through mesh sensitivity analysis by examining the relationship between the number of elements and contact force (Figure 3). The contact force decreased with increasing mesh density and gradually became less sensitive to further mesh refinement, indicating improved numerical stability. The validation of the finite element model in this study, the predicted mechanical responses were also qualitatively compared with published finite element study conducted under comparable orthodontic loading conditions, similar implant geometry, material properties. The magnitudes of the predicted Von Mises stress and displacement in this study should be similar with the previous study [10], as showed on Table 2. This agreement supports the validity of the present finite element model for comparative biomechanical evaluation.

3. Results and Discussion

3.1. Results

Figure 4 shows the maximum Von Mises stress obtained from the FEA of orthodontic mini-implants from CP-Ti, Ti6Al4V, and SS316L under orthodontic loads of 2 N, 4 N and 6 N. The Von Mises stress increased with increasing applied force for all materials. At an applied force of 2 N, the maximum Von Mises stress was 12.89 MPa for CP-Ti, 12.63 MPa for Ti6Al4V, and 14.81 MPa for 316L. When the load was increased to 4 N, the stress increased to 25.78 MPa, 25.27 MPa, and 29.63 MPa, respectively. At an applied force of 6 N, the highest stress was 38.67 MPa for CP-Ti, 37.90 MPa for Ti6Al4V and 44.44 MPa for SS316L.

Figure 5 presents the maximum displacement of orthodontic mini-implants fabricated from CP-Ti, Ti6Al4V and SS316L under applied loads of 2 N, 4 N and 6 N. Among all three materials, the maximum displacement increases as the applied load increases. CP-Ti and Ti6Al4V exhibited similarly displacement values. In contrast, SS316L demonstrated lower displacement values of 3.7×10^{-6} mm, 7.3×10^{-6} mm and 1.1×10^{-5} mm. The maximum displacement in this study was 1.5×10^{-5} mm, observed for Ti6Al4V and CP-Ti under the 6 N load.

Figure 6 illustrates the maximum contact pressure at the bone-implant interface of orthodontic mini-implants made of CP-Ti, Ti6Al4V and SS316L under applied loads of 2 N, 4 N, and 6 N. The contact pressure increased with increasing applied load. In the CP-Ti model, the contact pressure increased from 18 MPa at 2 N to 37 MPa at 4 N and 55 MPa at 6 N.

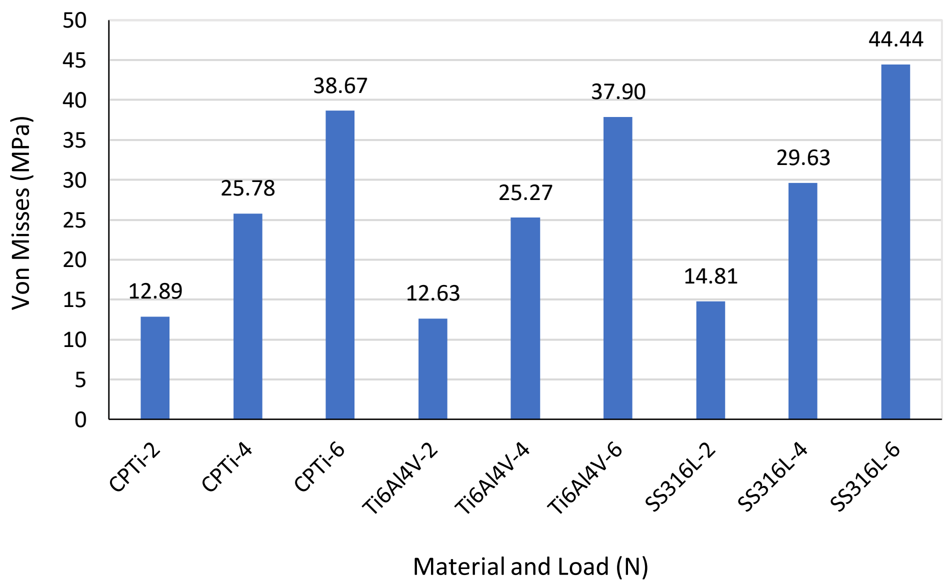


Figure 4. Comparison of maximum Von Mises stress in Orthodontic Mini-Implants made of CP-Ti, Ti6Al4V, and SS316L under applied loads of 2 N, 4 N, and 6 N.

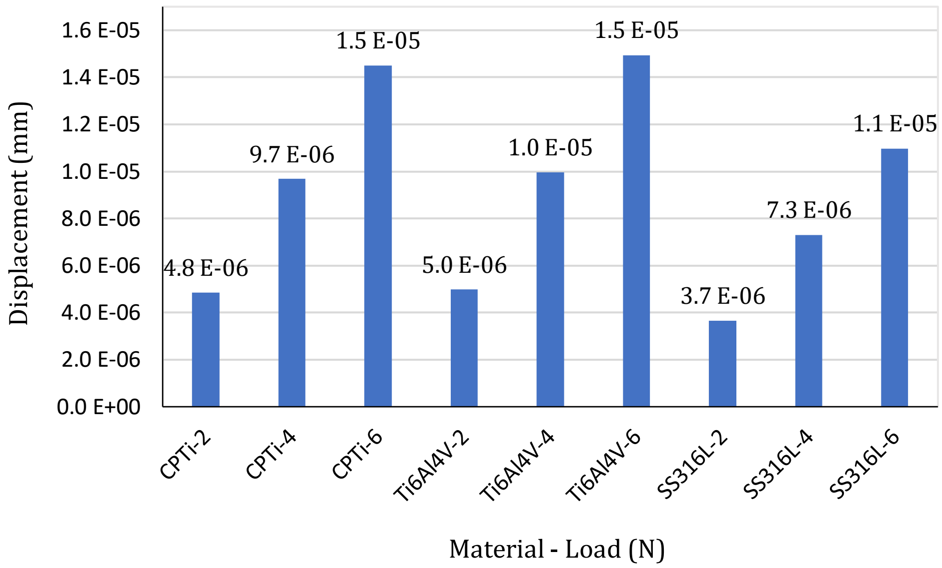


Figure 5. Maximum displacement of orthodontic mini-implants made of CP-Ti, Ti6Al4V, and SS316L under applied load of 2 N, 4 N, and 6 N.

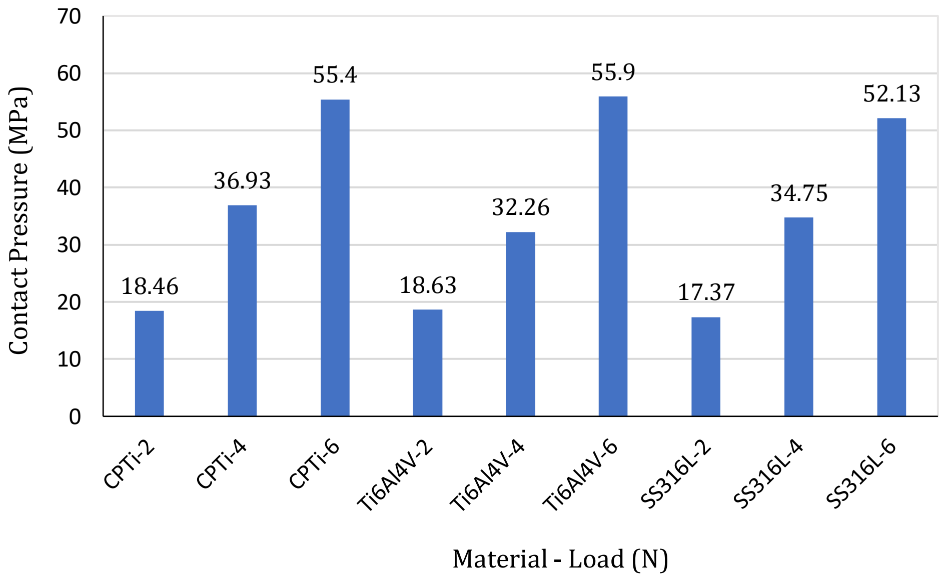


Figure 6. Maximum contact pressure at the bone-implant interface of orthodontic mini-implants made of CP-Ti, Ti6Al4V, and SS316L under applied load of 2 N, 4 N and 6 N.

Similarly, Ti6Al4V exhibited contact pressures of 19 MPa, 32 MPa, and 56 MPa, respectively. For SS316L the corresponding contact pressures were 17 MPa, 35 MPa and 52 MPa. At the lowest load (2 N), the materials produced similar contact pressures. At 4 N, CP-Ti showed the highest contact pressure (37MPa), whereas Ti6AL4V showed the lowest value (32 MPa). Under the highest applied load of 6 N, Ti6Al4V recorded the highest contact pressure, followed by CP-Ti and SS316L. Overall, the differences among the materials were relatively small compared with the increase caused by the applied load.

As summarized in Table 2, the predicted maximum Von Mises stress and displacement were comparable with values reported in the previous study. Furthermore, the present model reproduced the characteristic stress concentration at the implant neck adjacent to the cortical bone, which is consistent with the previous study. This agreement supports the validity for the developed finite element model for comparative biomechanical evaluation.

Table 2. Comparison of the present finite element model with previously published finite element studies.

Parameter	Rahimi et al. [10]	Rahimi et al. [10]	Rahimi et al. [10]	Present study
Material	6Al-4V titanium	6Al-4V titanium	6Al-4V titanium	Ti6Al-4V
Dia., screw length (mm)	1.6 ; 8	1.4 ; 8	1.6 ; 6	1.2 ; 6
Load (N)	2	2	2	2
Max. Von Mises Stress (MPa)	11.85	17.42	27.71	12.63
Max. Displacement (μm)	2.47	4.28	2.80	5.0

3.2. Discussion

The findings of this study indicate that both the magnitude of orthodontic loading and the choice of implant material significantly influence the biomechanical behavior at the bone–implant interface. The observed increase in stress and strain with higher loads is consistent with fundamental biomechanical principles, where lateral forces generate greater bending moments at the implant neck, leading to stress concentration in cortical bone, which plays a key role in primary stability.

The nearly proportional increase in Von Mises stress with increasing load indicates that all materials behaved within the linear elastic range during this study. This behavior is expected because orthodontic forces are relatively low and generally designed to produce controlled tooth movement without exceeding the elastic limit of the implant material.

Figure 7 shows Von Mises stress distribution under a 6 N load in orthodontic mini-implant models with different materials. Among the materials evaluated, Ti6Al4V exhibited the lowest Von Mises stress, followed by CP-Ti, and SS316L. At the highest applied load of 6 N, the stress in SS316L was about 17% higher than Ti6Al4V and 15% higher than CP-Ti. The differences between CP-Ti and Ti6Al4V were relatively small. Ti6Al4V showed the lowest stress, suggesting a slightly more favorable stress distribution. The maximum Von Mises stress recorded in this study is substantially lower than the yield strengths of the materials. Consequently, none of the materials is expected to undergo permanent deformation or mechanical failure under the simulated orthodontic forces.

The increase in Von Mises stress with increasing orthodontic load is consistent with previous finite element studies. Increasing orthodontic loading results in higher stress concentration around the mini-implant, with the highest stresses typically occurring in the cortical bone adjacent to the implant neck because this region experiences the greatest bending moment during lateral loading [13].

Figure 8 shows the comparison of displacement distributions under a 6 N load for orthodontic mini-implant models with different materials.

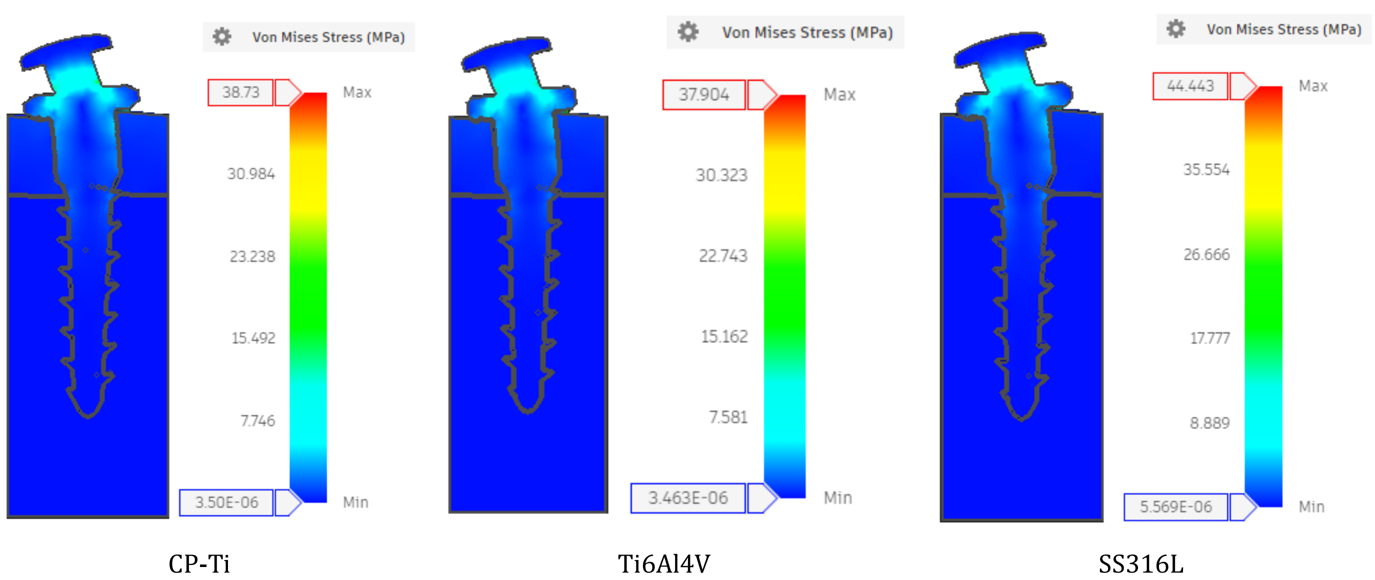
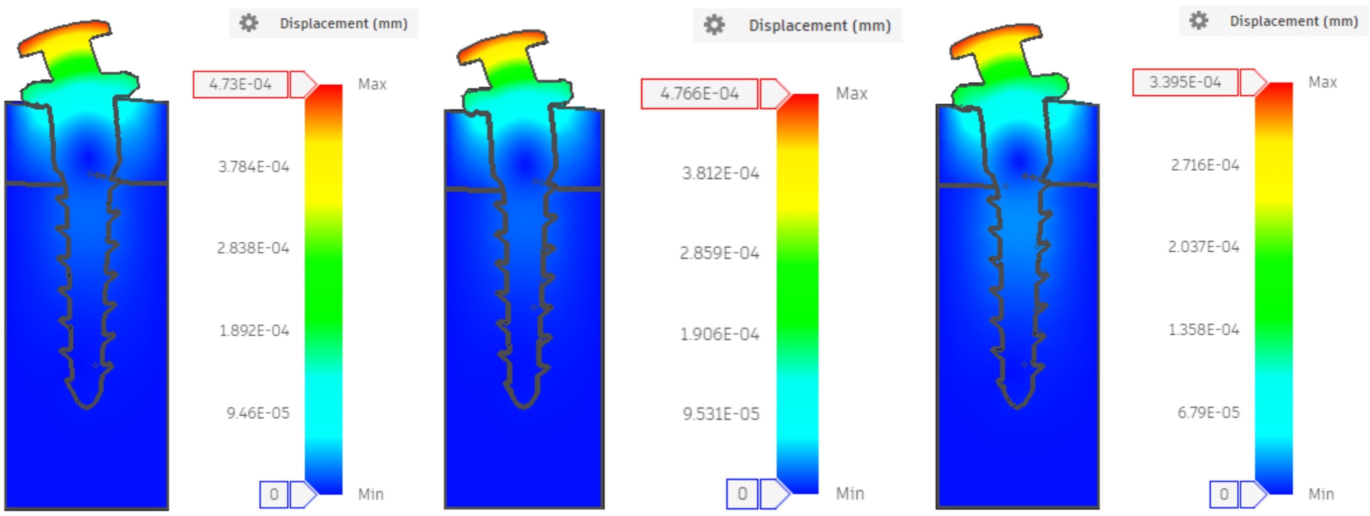


Figure 7. Von Mises stress distribution under a 6 N load in orthodontic mini-implant models with different materials.



CP-Ti Ti6Al4V SS316L

Figure 8. Comparison of displacement distributions under a 6 N load for orthodontic mini-implant models with different materials.

This study demonstrated that the displacement of orthodontic mini-implants increased progressively with increasing orthodontic load for all materials. This trend is still consistent with the assumptions of linear elastic behavior, in which deformation is directly proportional to the applied loads. The differences among the materials are primarily related to their elastic properties. In terms of the material properties used in this FEA study, SS316L has the highest Young's modulus (193 GPa), followed by CP-Ti (115.8 GPa) and Ti6Al4V (113.76 GPa). A higher Young's modulus indicates greater material stiffness, resulting in lower elastic deformation under the same loading conditions. Therefore, SS316L exhibited the smallest displacement at all applied loads. The displacement of SS316L is approximately 27% lower than titanium-based materials, reflecting its greater stiffness. The displacement values of CP-Ti and Ti6Al4V were almost identical throughout the loading conditions. This similarity is expected because the difference in Young's modulus is only 2 GPa or less than 2%.

The maximum displacement predicted by FEA was equal or less than 1.5×10^{-5} mm for all materials. That is extremely small and is unlikely to influence the clinical stability of orthodontic mini-implants. These temporary anchorage devices are required to remain sufficiently rigid to provide stable anchorage during orthodontic treatment. All three materials satisfy this mechanical requirement under loads up to 6 N. This result is consistent with previous finite element studies reporting that the orthodontic mini-implants exhibit minimal elastic deformation under clinically relevant orthodontic forces displacement value is substantially lower than the displacement generally considered capable of compromising the primary stability of orthodontic mini-implants [14].

The FEA showed that the contact pressure at the bone-implant interface increased progressively with increasing orthodontic load for all materials (Figure 9). The higher orthodontic forces produce higher compressive forces at the implant-bone interface, thereby increasing the contact pressure. Although the materials exhibited similar trends, slight differences in contact pressure were observed (the difference between the highest and lowest values was only 4 MPa). These differences are related to the elastic properties of the implant materials. The magnitude of the applied load has a greater influence on contact pressure than the choice of implant material within the investigated loading conditions. In terms of a biomechanical perspective, the contact pressure represents the compressive stress transmitted from the mini-implant to the surrounding cortical bone. Appropriate contact pressure is essential for maintaining primary stability because it enables effective load transfer between the implant and bone. Excessive localized contact pressure may increase compressive stress within the cortical bone and contribute to bone microdamage or localized bone remodeling under repeated loading. Similar observations have been reported in previous implant biomechanics studies, which indicate that excessive interface stress may adversely affect long-term implant stability by altering normal bone remodeling processes [15], [16].

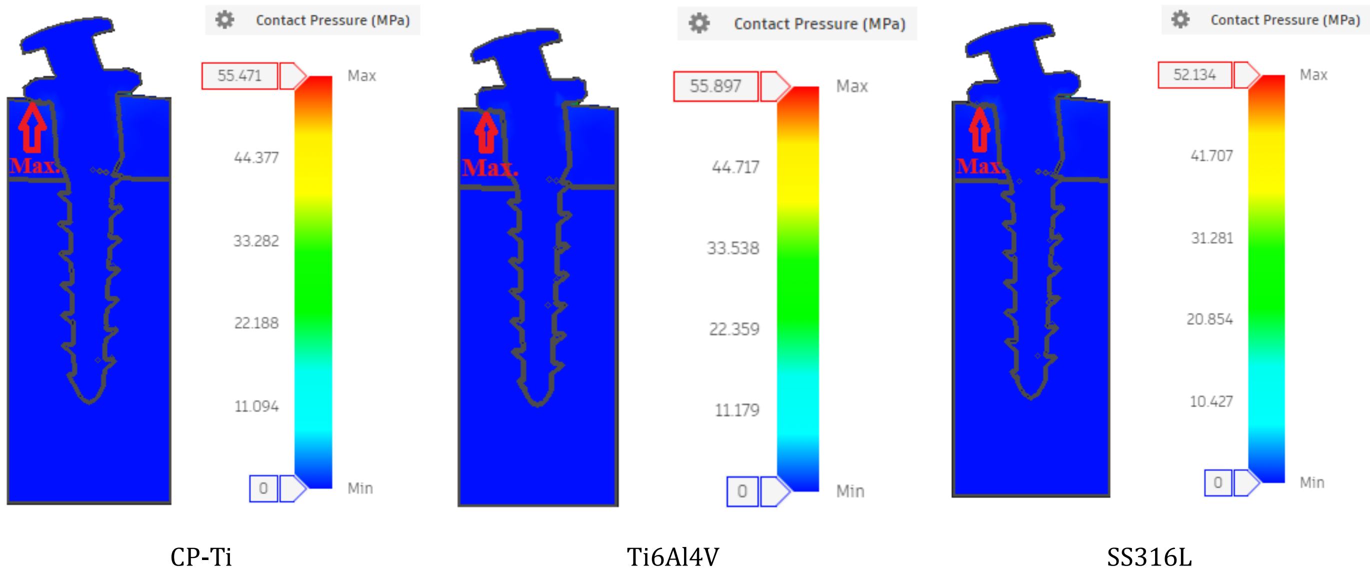


Figure 9. Location of the maximum contact pressure (MPa) in simulated orthodontic mini-implant models with different materials under a 6 N load.

When contact pressure results are interpreted together with the Von Mises stress and displacement analyses, a more comprehensive understanding of the biomechanical performance is obtained. SS316L exhibited the lowest displacement because of its higher stiffness, but also developed the highest Von Mises stress within the implant. In contrast, Ti6Al4V showed the lowest implant Von Mises stress while maintaining contact pressures comparable to CP-Ti and SS316L. These findings suggest that Ti6Al4V transfers orthodontic loads effectively to the surrounding bone without generating excessive stress concentrations within the implant structure.

Clinically, orthodontic mini-implants are commonly subjected to forces between 1 and 3 N, although higher forces may be applied in selected treatment mechanics. Even under the maximum simulated load of 6 N, the predicted contact pressures remained within a range that indicates stable force transfer across the implant–bone interface. Therefore, all three materials appear capable of providing adequate mechanical performance under typical orthodontic loading conditions. Materials with higher elastic modulus may exhibit lower deformation but can transfer a greater proportion of the applied load to the surrounding bone, potentially increasing localized contact pressure.

Overall, the finite element analysis indicates that implant material had only a modest influence on contact pressure, whereas the magnitude of the applied load was the primary factor governing the mechanical response at the bone–implant interface. Considering the combined results of contact pressure, Von Mises stress, and displacement, Ti6Al4V demonstrated the most balanced biomechanical performance, combining low implant stress with minimal deformation while maintaining effective load transfer to the surrounding bone.

4. Conclusions

This finite element analysis demonstrated that both implant material and orthodontic loading magnitude influence the biomechanical behavior of orthodontic mini-implants at the bone–implant interface. Increasing orthodontic load from 2 N to 6 N consistently increased Von Mises stress, displacement, and contact pressure in all evaluated materials, indicating a higher biomechanical demand and increased risk of microdamage at higher loading levels, particularly in cortical bone. Among the evaluated materials, Ti6Al4V showed the lowest Von Mises stress under all loading conditions, whereas SS316L showed the lowest displacement, reflecting its higher stiffness. CP-Ti displayed stress and displacement values comparable to Ti6Al4V, while producing contact pressures similar to those of the other materials. Although differences in contact pressure among the three materials were relatively small, the applied orthodontic load had a much greater influence on the biomechanical response than the choice of implant material. The scientific contribution of this study is in the comparative evaluation of three commonly used orthodontic mini-implant materials under identical geometric, boundary and loading conditions. The findings provide biomechanical evidence in selecting appropriate mini-implant materials and provide guidance for implant design optimization. Future studies experimental validation and clinical investigations are recommended to further confirm the computational findings. In addition, incorporating other designs, physiological parameters beyond material variation would provide a more comprehensive evaluation of the clinical application of orthodontic mini-implants.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that generative artificial intelligence (AI) or AI-assisted technologies were used solely to assist with grammar checking. It was limited to linguistic assistant. All scientific content, analyses, interpretations, and conclusions were developed, verified and reviewed by authors. The authors take full responsibility for the accuracy, originality, integrity, and final content of the manuscript, in accordance with the guidelines of the Committee on Publication Ethics (COPE).

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