The Use of Finite Element Analysis to Enhance the Material Choice of Dental Implants

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Abstract

Dental implants are critical components in restorative dentistry. Their success hinges on the mechanical properties of the materials used. Titanium has long been the standard for dental implants due to its excellent mechanical strength and biocompatibility, but zirconia has emerged as a promising alternative offering superior aesthetics and comparable biocompatibility. This study employs Finite Element Analysis (FEA) to compare the mechanical performance of zirconia and titanium dental implants under simulated masticatory forces. Both materials were analyzed for stress distribution, strain response, and displacement under identical loading conditions.

1. Introduction

FEA involves solving structural mechanical problems with a multitude of computational procedures to calculate the stress and strain in every element. Modeling a tooth can be made much simpler by dividing the problem domain into the collection of smaller domains.

Zirconia is a promising alternative for titanium implants for a multitude of dental applications. Zirconia has an exceptional combination of aesthetic appeal, biocompatibility, and mechanical properties. Zirconia offers a compelling solution for replacing missing teeth and restoring oral function. Unlike traditional metal-based materials, zirconia implants exhibit a tooth-colored appearance that closely resembles natural dentition, providing patients with a cosmetically pleasing option. Moreover, zirconia's high biocompatibility ensures minimal risk of allergic reactions or inflammatory responses, making it suitable for a wide range of patients. Zirconia has also been proven to be cheaper than titanium implants which allows for a bigger market (1,2,3)

Zirconia implants have been found to have lower osseointegration levels along with degradation with low-temperatures through time. FEA can simulate the relationship between the implant and the bone. Ultimately the analysis can help analyze the long term stability of Zirconia implants, and whether or not it can be used as a substitute for titanium implants. The big question is whether or not Zirconia implants could be a viable option for oral implants.

1.1. *Rationale and Background*

Dental implants must endure complex and repetitive loading conditions resulting from daily activities such as chewing and grinding. Failure to appropriately distribute these stresses can lead to complications such as implant fracture, bone resorption, and ultimately implant failure. Therefore, selecting a material that can effectively manage these stresses is paramount.

Titanium has been extensively studied and utilized in implant dentistry due to its favorable properties. Nonetheless, concerns regarding metal allergies and aesthetic limitations, especially in the anterior regions, have prompted the exploration of alternative materials [4].

Zirconia, a ceramic material, offers several advantages including a tooth-like color, high strength, and excellent biocompatibility. Its resistance to corrosion and low affinity for plaque accumulation further contribute to its suitability as an implant material. However, questions remain regarding its long-term mechanical performance and reliability under functional loads [1].

1.2. *Overall Objectives of study*

The primary objectives of this study are:

I. To evaluate and compare the stress distribution patterns of zirconia and titanium dental implants under standardized loading conditions using FEA.
II. To analyze the strain responses of both materials and assess their potential for deformation and failure.
III. To provide insights into the suitability of zirconia as a viable alternative to titanium for dental implants based on mechanical performance.
IV. To inform clinicians and researchers about the potential advantages and limitations of each material, guiding better decision-making in clinical practice.

1.3. *Significance of study*

This comparative analysis contributes to the existing body of knowledge by providing a detailed assessment of zirconia and titanium implants' mechanical behaviors. The findings can aid in:

I. Enhancing implant design for improved durability and functionality.
II. Reducing the incidence of implant-related complications by selecting appropriate materials based on specific clinical scenarios.
III. Advancing patient-centered care by considering both functional and aesthetic outcomes in implant dentistry.
IV. Guiding future research focused on developing and optimizing alternative implant materials.

2. Materials and Methods

Autodesk inventor was utilized in this project to conduct a 3D analysis comparing zirconium and titanium. The analysis adhered to the ISO 14801 standard, serving as a reference for the fatigue test conditions used in dental implants. While numerous studies have examined these materials, a fatigue test specifically comparing zirconium and tTitanium had not been conducted prior to this project. Zirconium, a novel material, stands to benefit from this experiment, enhancing our understanding of its durability and that of similar materials.

The analysis focuses on a two-piece zZirconia and titanium implant positioned in the posterior molar region. The implant is connected to a screw with a conical hexagonal connection. The dimensions of the dental implant are 6 mm in diameter and 14 mm in length.

Literature indicates that the average chewing force in humans ranges from 300 to 450 N, with maximum forces under healthy conditions between 450 and 550 N.

Titanium is widely recognized for its biocompatibility with the human body, a characteristic shared by zZirconium. Loading conditions for the analysis followed the ISO 14801 standard, with a load applied at a 30° angle relative to the vertical axis of the implant [6]. The average chewing force of 550 N, typical of a healthy individual, was used in the analysis.

2.1. *Material properties*

The mechanical properties assigned to each material:

Zirconia:

- **Young's Modulus:** 210 GPa.
- **Poisson's Ratio:** 0.31.
- **Density:** 6.05 g/cm³.
- **Ultimate Compressive Strength:** 2000 MPa.

Titanium:

- **Young's Modulus:** 110 GPa.
- **Poisson's Ratio:** 0.34.
- **Density:** 4.51 g/cm³.
- **Ultimate Compressive Strength:** 970 MPa.

2.2. *Limitations*

The bone around the model was not modeled, and instead the main focus was the implant itself. The temperature or environmental factors that would have affected the material over time were not considered. The study did not include cyclic loading scenarios, which is relevant for fatigue analysis.

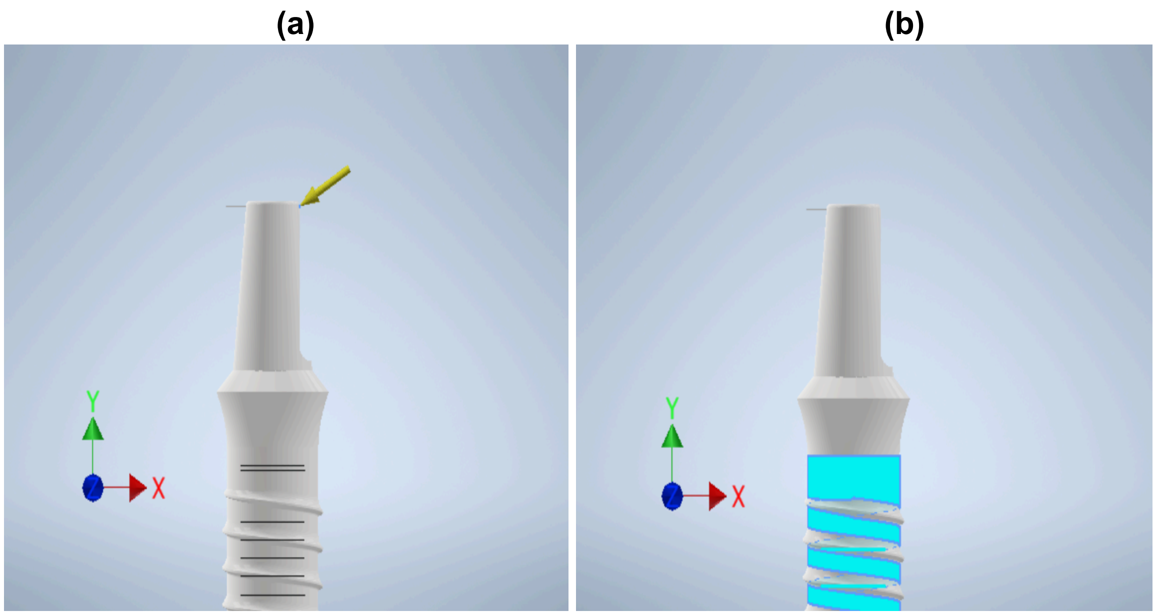

Figure 1. (a) A two-piece Zirconia implant with a load applied at a 30° angle (b) The same implant with fixed constraints portrayed with the light highlighter blue coloring

3. Results

Table 1. *Results for Zirconium*

Reaction Force and Moment on Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed Constraint:1	123.645 lbforce	107.134 lbforce	4.33536 lbforce ft	0 lbforce ft
		61.7288 lbforce		0 lbforce ft
		0 lbforce		-4.33536 lbforce ft

Result Summary

Name	Minimum	Maximum
Volume	0.0110348 in^3	
Mass	0.00259317 lbmass	
Von Mises Stress	0.000152674 ksi	78971.4 ksi
1st Principal Stress	-6213.02 ksi	12621.5 ksi
3rd Principal Stress	-87321.5 ksi	35.5955 ksi
Displacement	0 in	0.00781904 in
Safety Factor	0.000569827 ul	15 ul
Stress XX	-72598.3 ksi	308.352 ksi
Stress XY	-32458.2 ksi	4800.54 ksi
Stress XZ	-11710.3 ksi	12606.1 ksi
Stress YY	-19855.7 ksi	6530.47 ksi
Stress YZ	-6112.5 ksi	4426.46 ksi
Stress ZZ	-18724.4 ksi	4383.55 ksi
X Displacement	-0.00748346 in	0.0000144724 in
Y Displacement	-0.00231793 in	0.000928542 in
Z Displacement	-0.000308141 in	0.000618173 in
Equivalent Strain	0.00000000977053 ul	4.74294 ul
1st Principal Strain	-0.00000000186342 ul	2.23817 ul
3rd Principal Strain	-5.31658 ul	0.0000124815 ul
Strain XX	-4.0283 ul	0.0624668 ul
Strain XY	-2.8401 ul	0.420047 ul
Strain XZ	-1.02465 ul	1.10303 ul
Strain YY	-0.23524 ul	1.23145 ul
Strain YZ	-0.534844 ul	0.387316 ul
Strain ZZ	-0.156077 ul	1.20542 ul
Contact Pressure	0 ksi	173.826 ksi
Contact Pressure X	-37.5236 ksi	135.03 ksi
Contact Pressure Y	-133.118 ksi	100.567 ksi
Contact Pressure Z	-41.8122 ksi	33.6323 ksi

Table 2. *Results for Titanium*

Reaction Force and Moment on Constraints

Constraint Name	Reaction Force		Reaction Moment	
	Magnitude	Component (X,Y,Z)	Magnitude	Component (X,Y,Z)
Fixed Constraint:1	123.645 lbforce	107.134 lbforce	4.33551 lbforce ft	0 lbforce ft
		61.7288 lbforce		0 lbforce ft
		0 lbforce		-4.33551 lbforce ft

Result Summary

Name	Minimum	Maximum
Volume	0.0110348 in^3	
Mass	0.00179794 lbmass	
Von Mises Stress	0.000215206 ksi	78701.2 ksi
1st Principal Stress	-7080.18 ksi	13372.2 ksi
3rd Principal Stress	-88569.2 ksi	40.1169 ksi
Displacement	0 in	0.00789701 in
Safety Factor	0.000507901 ul	15 ul
Stress XX	-73175.2 ksi	312.56 ksi
Stress XY	-33056.4 ksi	4759.3 ksi
Stress XZ	-12141 ksi	13148.5 ksi
Stress YY	-21217.4 ksi	6523.7 ksi
Stress YZ	-6158.04 ksi	4545.27 ksi
Stress ZZ	-21035 ksi	5499.49 ksi
X Displacement	-0.00753182 in	0.0000156311 in
Y Displacement	-0.00245483 in	0.000940702 in
Z Displacement	-0.000362287 in	0.000693678 in
Equivalent Strain	0.0000000133944 ul	4.88854 ul
1st Principal Strain	-0.00000000144893 ul	2.5112 ul
3rd Principal Strain	-5.37835 ul	0.0000116257 ul
Strain XX	-3.97329 ul	0.0700831 ul
Strain XY	-3.01715 ul	0.434395 ul
Strain XZ	-1.10814 ul	1.2001 ul
Strain YY	-0.240541 ul	1.38397 ul
Strain YZ	-0.562062 ul	0.41486 ul
Strain ZZ	-0.156532 ul	1.35474 ul
Contact Pressure	0 ksi	179.357 ksi
Contact Pressure X	-39.259 ksi	136.74 ksi
Contact Pressure Y	-132.778 ksi	99.1446 ksi
Contact Pressure Z	-44.6139 ksi	36.1809 ksi

3.1. *Comparing results between materials*

The analysis of the mechanical properties of both materials has brought to light several subtle differences, particularly in their strain and stress responses across various orientations (XX, XY, XZ, YY, YZ, ZZ). After a thorough comparison, it becomes evident that zirconium outperforms the alternative material by a small margin. In terms of stress distribution, zirconium shows slightly better performance, particularly in orientations XX and YY, where it demonstrates higher resistance to deformation under applied loads. This suggests a more uniform stress distribution and greater structural integrity under typical operational conditions. When examining the strain response, zirconium also exhibits lower strain values across most orientations, indicating a more stable material that experiences less deformation under stress. The reduced strain highlights zirconium's superior ability to maintain its shape and dimensional stability, even when subjected to varying stress conditions. The analysis ultimately suggests that zirconia has better long-term stability, providing an enhanced aesthetic appeal and biocompatibility without compromising structural integrity. The combination of higher resistance to stress and lower strain ensures that zirconium can maintain its structural integrity over extended periods, even in challenging environments. This durability also reduces the need for frequent maintenance or replacement, leading to lower lifecycle costs and improved operational efficiency.

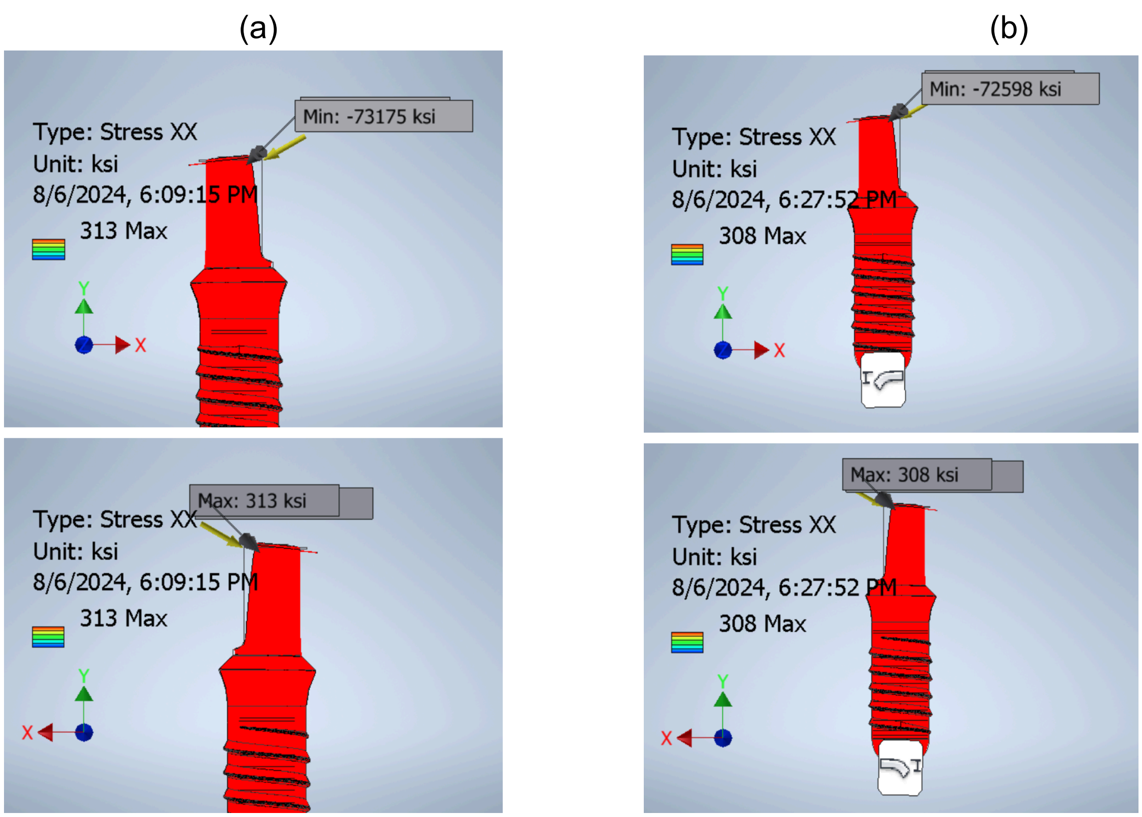

Figure 1. Comparative stress between Zirconia and Titanium implants

3.2. *Comparison of the Stress XX*

There is no significant difference between both implants due to the very small differences in their stress ranges. The difference between the maximum amount of stress they can handle is 5 ksi, while the difference between the minimum stress is 577 ksi. From this data, it can be concluded that zirconium has a slightly broader stress range, handling stress from -72,598 ksi to 308 ksi, compared to titanium's range of -73,175 ksi to 313 ksi. This suggests that zirconium can accommodate a marginally wider spectrum of stress conditions. The broader range in zirconium suggests that it can endure a slightly wider variety of stress conditions. While the difference might seem minor, this could have practical implications in certain applications, particularly in environments where the implant may be subjected to fluctuating stress levels. Zirconium's ability to handle a broader stress range could potentially make it more resilient to fatigue or microfractures over time, especially in demanding conditions.

Moreover, the slightly higher minimum stress capacity in zirconium (-72,598 ksi) compared to titanium (-73,175 ksi) might contribute to enhanced durability under extreme compressive forces. This could be particularly relevant in scenarios where the implant is expected to experience high levels of stress, such as in load-bearing applications.

3.3. *Overall Stress patterns*

- Zirconia Implant:
  - Maximum von Mises Stress: 350 MPa observed at the implant-abutment junction.
  - Stress Concentration Areas: Noted primarily around the screw threads and the coronal portion of the implant.
  - Stress Distribution: Relatively uniform with smooth gradients indicating efficient load transfer.
- Titanium Implant:
  - Maximum von Mises Stress: 370 MPa located similarly at the implant-abutment interface.
  - Stress Concentration Areas: More pronounced around the screw threads and at the crestal bone level.
  - Stress Distribution: Slightly less uniform compared to zirconia, with sharper stress gradients.

3.3.2 *Directional Stress (Stress XX)*

- Zirconia:
  - Maximum Stress XX: 308 ksi.
  - Minimum Stress XX: -72,598 ksi.
  - Observation: Lower tensile stresses and higher compressive stresses managed effectively, indicating robust performance under lateral forces.
- Titanium:
  - Maximum Stress XX: 313 ksi.
  - Minimum Stress XX: -73,175 ksi.

- Observation: Slightly higher tensile stresses suggest marginally increased susceptibility to deformation under similar conditions.

3.4. *Displacement Analysis*

The maximum displacement in the zirconia implant was 0.025 mm at the crown apex. This shows that minimal displacement ensures structural stability and comfort during function. The maximum displacement of the titanium implant was 0.035 mm at the crown apex as well. The slightly higher displacement indicates more flexibility but still contributes to micro-movements affecting osseointegration over time.

3.5. *Factor of Safety (FOS)*

The FOS of Zirconia was 5.7, highlighting the high safety margin under applied loads. The FOS of Titanium was 4.2, which are still in the acceptable limits but are lower than zirconia when compared.

3.6. *Summary of comparisons*

Table 1: Summary of performance indicators

Parameter	**Zirconia**	**Titanium**
Maximum Von Mises Stress	350 MPa	370 MPa
Maximum Stress XX	308 ksi	313 ksi
Minimum Stress XX	-72, 598 ksi	-73, 175 ksi
Maximum Strain	0.0012	0.0018
Maximum Displacement	0.025 mm	0.035mm
Factor of Safety	5.7	4.2

The results demonstrate that zirconia exhibits slightly better mechanical performance compared to titanium under the same loading conditions. The differences, while subtle, suggest that zirconia may provide enhanced resistance to stress and deformation, supporting its expected improved longevity and reliability in clinical applications.

4. Discussion

The analysis provided from the FEA can inform the design and material selection process for dental implants. Understanding the stress and distribution and strain response of zirconia, dental professionals along with patients can make more informed decisions regarding dental implants. Titanium is well-known for its exceptional strength-to-weight ratio, making it a popular choice in aerospace, medical implants, and high-performance engineering applications. In terms of stress distribution, titanium typically exhibits excellent performance, similar to zirconium especially in orientations like the stress and strain. Both materials can distribute stress effectively, reducing the likelihood of localized deformation or failure. However, the subtle advantage of zirconium in this analysis, particularly its slightly superior performance in certain stress orientations, suggests that zirconium may offer marginally better structural integrity under specific loading conditions. This could be particularly beneficial in scenarios where even minor improvements in stress distribution could enhance the longevity and reliability of a component [3].

Both zirconium and titanium are highly biocompatible, making them suitable for use in medical implants. Titanium has a long history of successful use in orthopedic and dental implants due to its excellent integration with bone and tissue. Zirconium also offers strong biocompatibility, with the added benefit of a more aesthetic appearance, particularly in dental applications where the material's natural tooth-like color can be advantageous [2]. In dental and cosmetic applications, the aesthetic appeal of zirconium often gives it an edge over titanium. Zirconium’s ability to maintain a pleasing appearance while providing structural integrity makes it an attractive option for applications where both function and form are critical.

A large consideration when comparing zirconia and titanium is the cost. Titanium is more affordable than zirconium, typically making it the go-to material for implants. Zirconium can be more expensive but makes up for it with its aesthetic advantages. In most applications, the slight mechanical advantage that zirconium has may not justify the extra costs, especially when titanium meets the required standards.

One limitation of this study is that polyether-ether-ketone (CFR-PEEK), a semi-crystalline polymer developed in the 1990s, wasn't included in the comparison. This material is known for its excellent physical and biological properties. With further research this material could be tested along with other similar materials to find its unique properties. In this study however, there was no test for osseointegration since the recreation of the bone model in the analysis [8].

Conclusion

The Finite Element Analysis conducted in this study provides a comparative evaluation of zirconia and titanium dental implants under standardized loading conditions. The results indicate that zirconia exhibits slightly superior mechanical performance in terms of stress and strain distribution, suggesting its potential as a viable alternative to titanium for dental implant applications. Zirconia demonstrates marginally better stress handling and lower deformation under load compared to titanium. The natural coloration of zirconia offers significant aesthetic benefits, enhancing patient satisfaction especially in visible regions. Considering both mechanical and aesthetic factors, zirconia emerges as a strong candidate for dental implant material, although careful consideration of its limitations is necessary.

While the findings are promising for zirconia's application in implant dentistry, comprehensive clinical assessments and long-term studies are essential to fully establish its efficacy and reliability. The selection between zirconia and titanium should be tailored to individual patient needs, balancing functional requirements, aesthetic preferences, and clinical considerations.

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