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ORIGINAL RESEARCH

STATIC FORCE ANALYSIS OF DENTAL IMPLANT CONNECTORS USING FINITE ELEMENT ANALYSIS

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ABSTRACT

This study evaluates the biomechanical performance of dental implant connectors-hexagonal, octagonal, and one-unit systems—under static loading using finite el- ement analysis (FEA) in SolidWorks. Three-dimensional models of titanium im- plants were subjected to a 100 N force at an angle per ISO 14801 standards, with the implant base fixed to simulate jawbone conditions. Stress (Von Mises), dis- placement, and strain were analyzed to assess load-bearing capacity and mechan- ical stability. Results indicate that two-unit systems (hexagonal and octagonal) exhibit superior load-bearing capacity compared to the one-unit system, with the hexagonal design showing marginally better stress distribution. However, differ- ences between hexagonal and octagonal connectors were minimal. The one-unit system displayed higher stress and deformation, potentially due to its thinner, longer design. These findings suggest that connector design significantly influences implant performance, with implications for clinical applications. Future studies should validate these results with experimental data and explore the impact of implant dimensions.

***Keywords**:* Dental implant, connector design, osseointegration, finite element analysis, SolidWorks, static force

1 INTRODUCTION

Dental implants are a cornerstone of modern restorative dentistry, offering a reliable solution for tooth replacement through osseointegration, the direct fusion of implant material with bone[1]. Since the discovery of titanium's osseointegration properties in the 1950s, implant designs have evolved significantly, with improvements in materials, surface treatments, and connector systems[2]. The implant-abutment interface is a critical factor in implant success, as it influences stress distribution, mechanical stability, and long-term durability[3]. Early external connections, where the abutment covered the implant, have largely been replaced by internal connections, such as hexagonal and octagonal designs, which aim to enhance stability and reduce prosthetic failures [4].

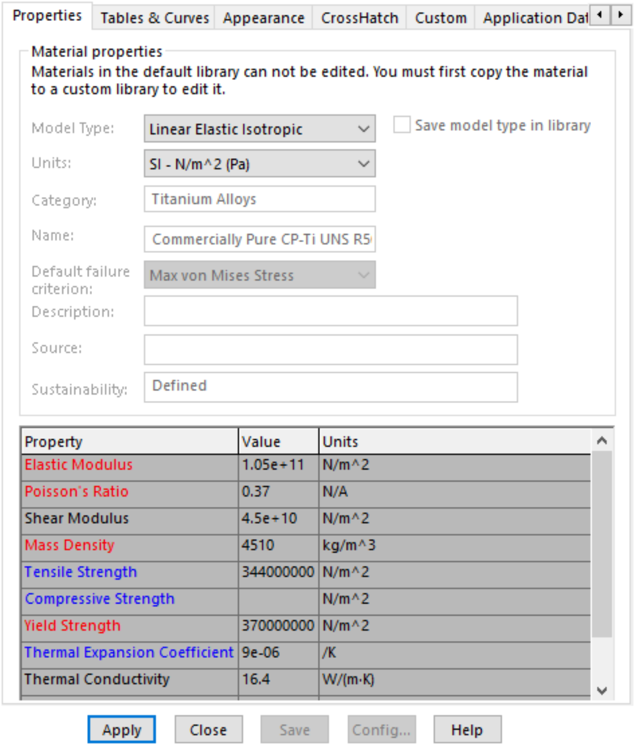
Despite these advancements, the optimal connector design remains debated. Hexag- onal connections are widely used due to their proven mechanical performance, while octagonal designs are emerging as potential alternatives [5]. Additionally, one-unit (monolithic) implants, which integrate the implant and abutment, offer simplified surgical procedures but may compromise flexibility[3]. Finite element analysis (FEA) has become a valuable tool for evaluating implant biomechanics, allowing researchers to simulate stress, displacement, and strain under controlled conditions (6). This study uses FEA to compare the biomechanical performance of hexagonal, octagonal, and one-unit dental implant systems under static loading, addressing the gap in comparative data on these connector designs.

2.MATERIALS AND METHODS

2.1 FEA Model Design

Three-dimensional models of dental implants were created using SolidWorks (Dassault Systèmes, USA). Two-unit systems with internal hexagonal and octagonal connectors and a one-unit (monolithic) system were designed based on standard titanium implant specifications (Young's modulus: 110 GPa, Poisson's ratio: 0.34)according to the table below.

The implant dimensions were as follows: two-unit implants (3.7 mm diameter, 12 mm length) and one-unit implants (3.7 mm diameter, 20 mm length). The abutments for two-unit systems were modeled with corresponding hexagonal or octagonal interfaces, while the one-unit implant integrated the abutment.



Property	Value	Units
Elastic Modulus	1.05e+11	N/m^2
Poisson's Ratio	0.37	N/A
Shear Modulus	4.5e+10	N/m^2
Mass Density	4510	kg/m^3
Tensile Strength	344000000	N/m^2
Compressive Strength		N/m^2
Yield Strength	370000000	N/m^2
Thermal Expansion Coefficient	9e-06	/K
Thermal Conductivity	16.4	W/(m·K)

Table 1 (the properties of the titanium samples)

2.2 FEA Setup

The implant base was fixed to simulate anchorage in the jawbone.Using the SolidWorks program to simulate two-unit dental implant system that involve most important designs of the internal dental implant joint, the hexagonal design and The octagonal design, with one-unit dental implant system where a force of 100 Newton will be applied to All designs at a pre-specified angle according to ISO 14801 to know the results of the physical properties of each joint, noting that each of the implants is internally designed.

The dental implant tip was fixed from the bottom to simulate its position in the jaw. Then, a force of 100 N was applied through the program's simulator for each design, taking into account the shape of the abutment for each one, and at a pre-designated angle according to ISO 14801

The simulation outputs included Von Mises stress (MPa), displacement (mm), and strain.

Each model was fixed at the bottom, and then a force of 100 N was applied to the upper part to simulate jaw movement, as shown in the diagram below.

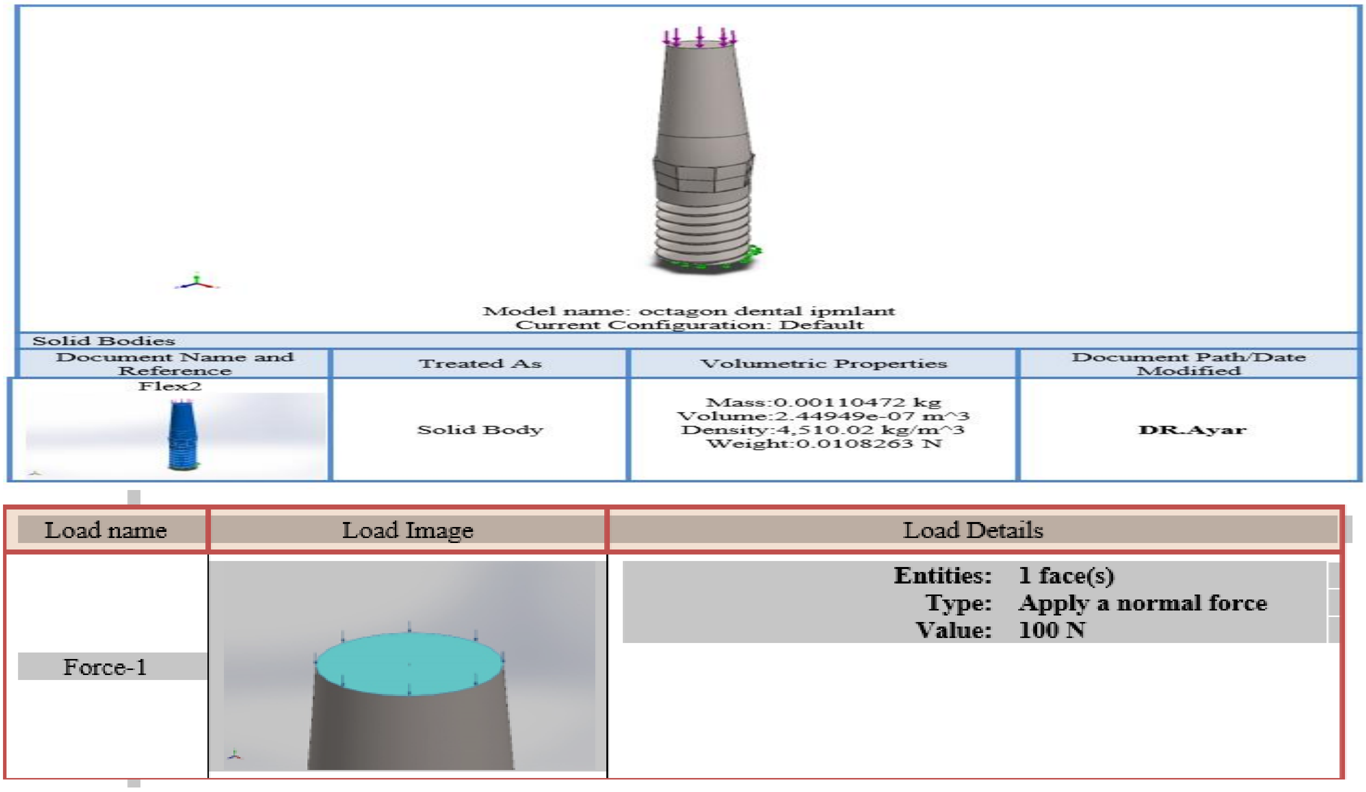
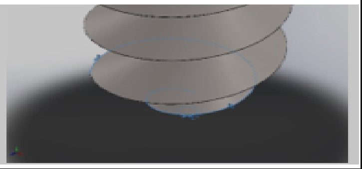


Figure 1. The direction of the applied force

Loads and Fixtures

Fixture name	Fixture Image	Fixture Details
Fixed-1		Entities: 2 edge(s) Type: Fixed Geometry

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	-8.77703	73.3937	-10.1863	74.6152
Reaction Moment(N.m)	0	0	0	0

Figure 2. The fixed surface

2.2 Analysis

Stress distribution, maximum displacement, and strain were calculated for each implant design. Results were visualized using color-coded stress and displacement maps. Due to the absence of experimental validation, a sensitivity analysis was performed to assess the impact of mesh size and boundary conditions on results. And the properties was according to the table below

Table 3. Soild works program study specification

Study name	Static 1
Analysis type	Static
Mesh type	Solid Mesh
Thermal Effect:	On
Thermal option	Include temperature loads
Zero-strain temperature	298 Kelvin
Include fluid pressure effects from SOLIDWORKS Flow Simulation	Off
Solver type	FFEPlus
In-plane Effect:	Off
Soft Spring:	Off
Inertial Relief:	Off
Incompatible bonding options	Automatic
Large displacement	Off
Compute free body forces	On
Friction	Off
Use Adaptive Method:	Off

3.RESULTS

All implants were analyzed using the SolidWorks simulation program. Stress results for the hexagonal joint implant were better than for the octagonal one, with only minor differences in displacement and deformation. However, stress and deformation in the one-piece system were significantly higher (Note that the dimensions of the implants with the two-piece system were similar, while the implant with the one-piece system was longer), as shown in the table and figures attached below, which contain the test results.

Note: Stress helps determine whether there will be permanent deformation in the metal and is represented by Von Mises Stress. Displacement refers to the rate at which an object moves when a force is applied to it, and finally, strain represents the change in length compared to the original length

1-A-Hexagon

Name	**Type**	**Min**	**Max**
Stress1	VON: von Mises Stress	3.361e+05N/m^2 Node: 7880	3.376e+08N/m^2 Node: 14173
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	1.730e-01mm Node: 7553
Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.021e-05 Element: 4304	2.233e-03 Element: 7704

B- Octagon

Name	**Type**	**Min**	**Max**
Stress1	VON: von Mises Stress	2.396e+05N/m^2 Node: 8132	3.611e+08N/m^2 Node: 14729
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	2.061e-01mm Node: 1127
Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	3.351e-06 Element: 1909	2.422e-03 Element: 4057

2- One unit-system (compressive) dental implant

Name	**Type**	**Min**	**Max**
Stress1	VON: von Mises Stress	1.259e+06N/m^2 Node: 21799	2.928e+10N/m^2 Node: 27478
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 649	1.359e+01mm Node: 17308
Name	Type	Min	Max
Strain1	ESTRN: Equivalent Strain	1.445e-05 Element: 4148	1.385e-01 Element: 4359

Figures illustrate stress and displacement distributions for each design

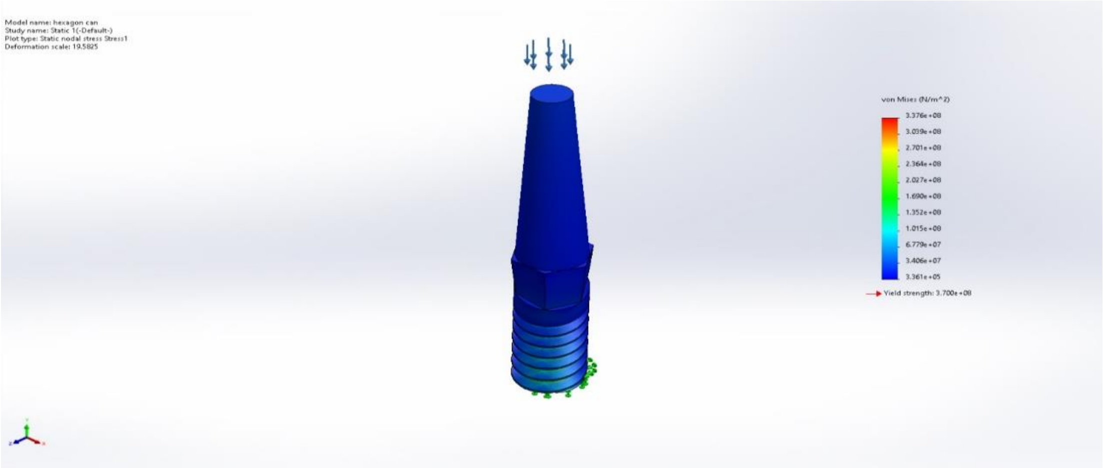


Figure 3. A – Stress of two-unit system with hexagonal connection design

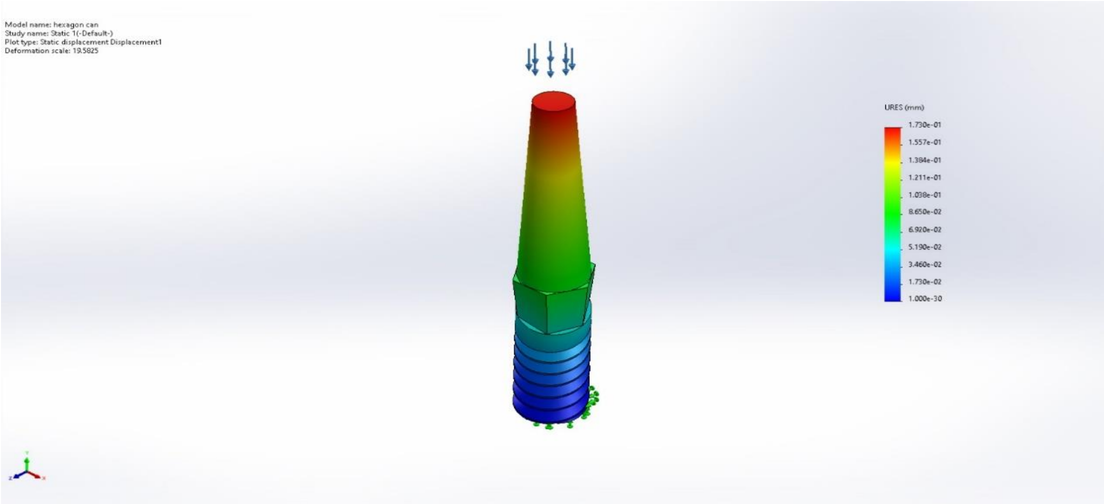


Figure 3.B– displacement of the two-unit system with hexagonal connection design

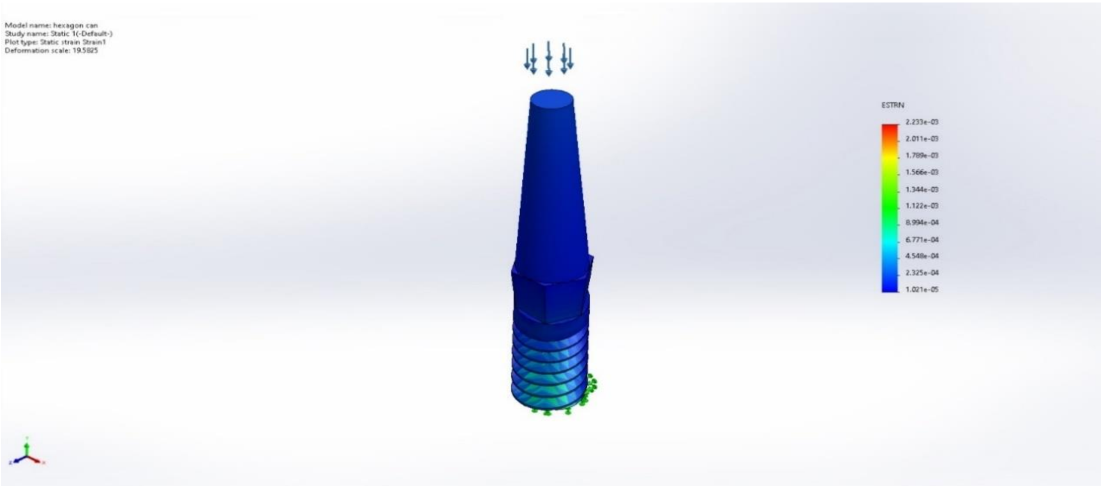


Figure 3. C – strain of the two-unit system with hexagonal connection design

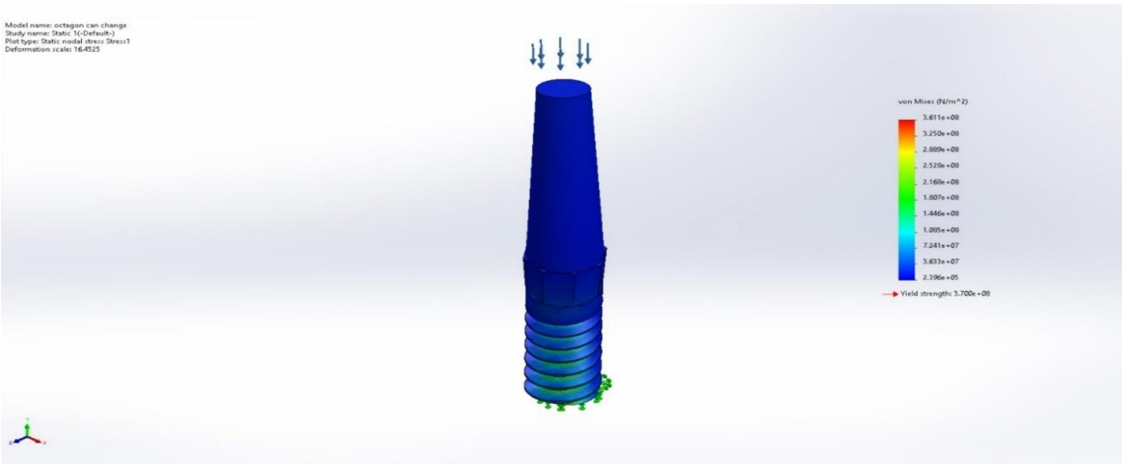


Figure. 4 A – stress of the two-unit system with octagonal connection design

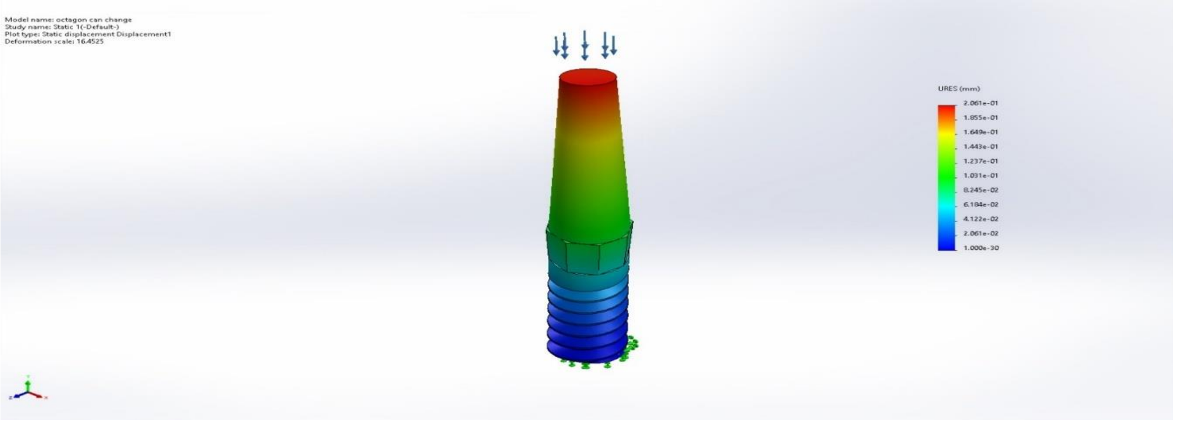


Figure 4. B–displacement of the two-unit system with octagonal connection design

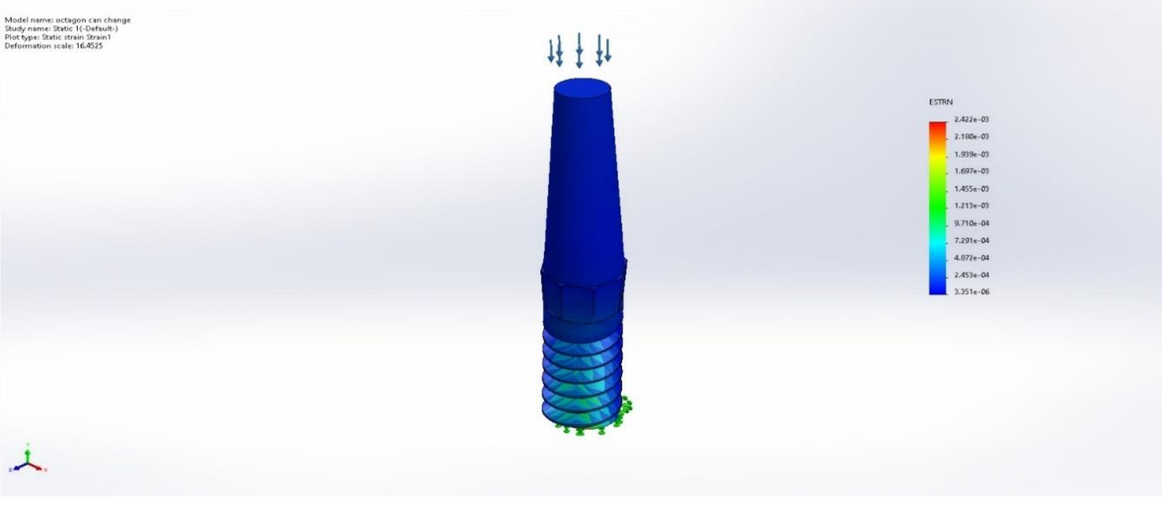


Figure 4. C–strain of the two-unit system with octagonal connection design

Figure 5. A-Stress of the one-unit system (compressive) design

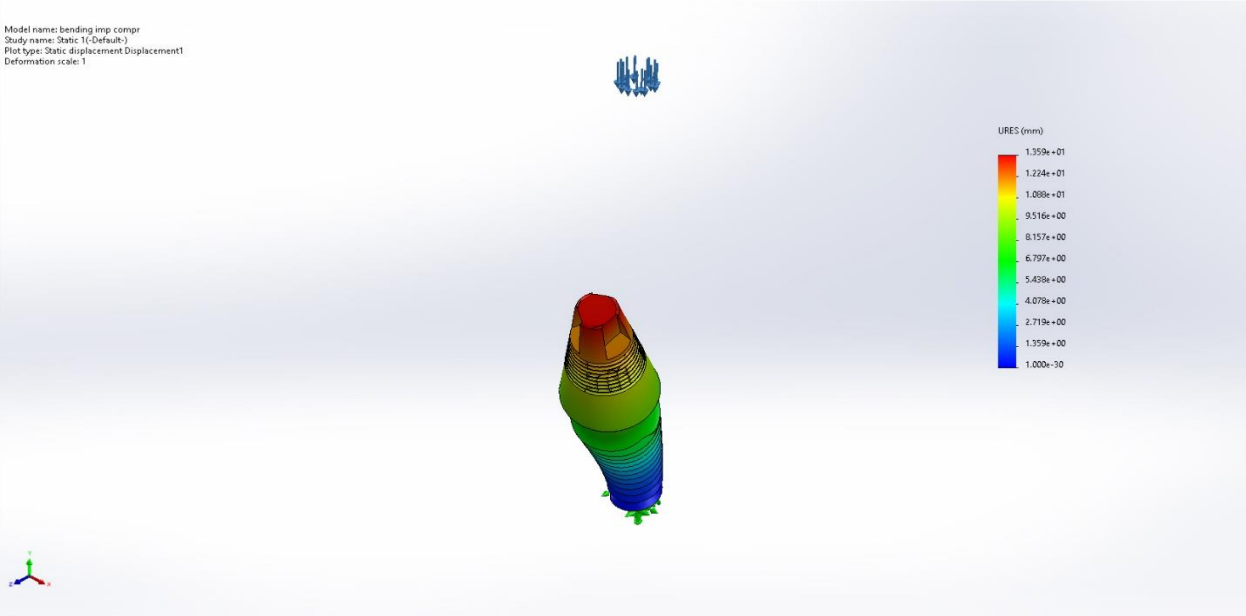


Figure 5 B-Displacement of the one-unit system (compressive) design

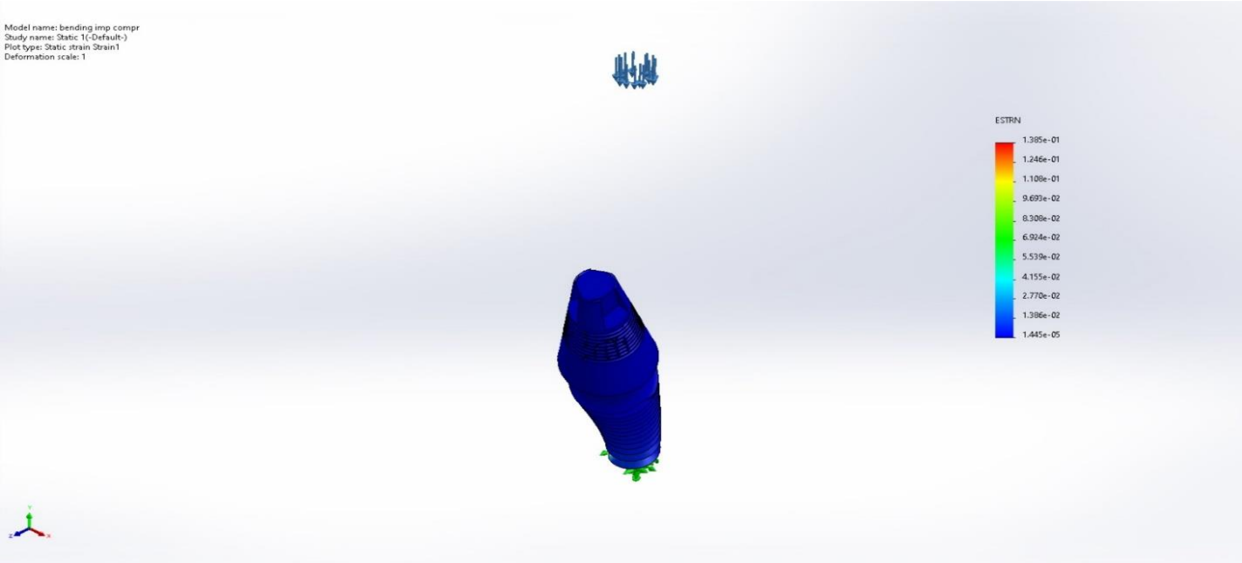


Figure 5 C Strain of the one-unit system (compressive) design

The hexagonal design showed uniform stress distribution, while the octagonal design had slightly higher stress concentrations at the connector edges. The one-unit system exhibited pronounced stress peaks at the neck region, suggesting potential vulnerability to deformation.

4.1 DISCUSSION

This study demonstrates that connector design significantly influences the biomechanical performance of dental implants. The hexagonal connector outperformed the octagonal design in stress distribution, consistent with prior studies reporting lower strain values for hexagonal interfaces [5,7]. However, the differences between hexagonal and octagonal designs were minimal, suggesting that both are viable for two-unit systems. The one- unit system's higher stress and deformation may be attributed to its thinner diameter and longer length, which increase susceptibility to bending forces [3]. The flexible neck of the one-unit implant, not modeled in SolidWorks, may further influence real-world performance.

The findings align with the literature emphasizing the importance of implant-abutment interface design[7]. However, the lack of experimental validation limits the generalizability of these results [8]. Additionally, the study did not account for dynamic loading or bone-implant interactions, which are critical for clinical relevance [9].

Future research should validate FEA models with in vivo or experimental data and explore the impact of implant dimensions and surface treatments on biomechanical outcomes.

The success and durability of dental implant treatments are greatly influenced by their design. In order to maximize strength, interfacial stability, and load transfer, the ideal design takes into account a number of variables, such as geometry, mechanical properties, and surface characteristics[10]. Although there isn't a single "optimal" design criterion, a number of crucial components enhance osseointegration and overall implant success.

One important element in improving implant performance is surface modifications. Techniques for nanosurface engineering have demonstrated promise in enhancing the bioactivity of titanium implants and encouraging osteogenesis around them [11]. Materials such as titanium, zirconia, and polyether ketone have been subjected to a variety of physical, chemical, and biological processes to promote osseointegration and reduce bacterial colonization[12]. The SLActive surface, for example, has shown promise an in encouraging osseointegration in its early stages, whereas the TiUnite surface has demonstrated the best overall impact on stability and osseointegration[13]. To sum up, the optimal dental implant design incorporates a number of elements, such as thread design, material composition, and surface modifications. More efficient and customized implant solutions are becoming possible thanks to innovations like nanotechnology, 3D printing, and smart surfaces [14]. According to Jebelli et al. (2024), the combination of growth factors and bioactive materials has the potential to completely transform patient satisfaction and treatment results. In order to improve overall implant performance and long-term success, research is still focused on creating dependable, affordable techniques that combine several purposes, like osteoconductive and antibacterial qualities [15].

Both hexagonal and octagonal internal dental implant connections have advantages, according to the context given, but the hexagonal design seems to have more evidence to support its efficacy. In terms of mechanical resistance and stress distribution, internal hexagonal connections have demonstrated promising outcomes. When compared to other implant systems, the 3i implant system with a hex and a 12-point double internal hexagonal connection showed superior stress distribution and reduced displacement, according to Tang[16]. (2012).Additionally, according to Balik et al. [18], out of all the connection designs, the internal hexagonal implant-abutment connection system displayed the lowest strain values.

Although octagonal designs are mentioned, their performance is not as well described.Perriard and colleagues (2002) talk about an
Straumann added an octagonal internal key to a morse-taper configuration, but the study found no discernible difference in mechanical resistance between the internally keyed and standard connectors [17].

In conclusion, internal hexagonal connections may have advantages in terms of stress distribution and mechanical performance, even though both octagonal and hexagonal internal connections can be useful. But it's crucial to remember that implant success is dependent on a number of variables other than the connection design, such as implant material, surface treatment, and patient-specific factors

This FEA study highlights the superior load-bearing capacity of two-unit dental implant systems with hexagonal and octagonal connectors compared to the one-unit system. The hexagonal design showed slightly better stress distribution, but both two-unit designs outperformed the one-unit system, which exhibited higher stress and deformation. These findings underscore the importance of connector design in optimizing implant performance. Clinically, two-unit systems may be preferred for cases requiring high mechanical stability, while one-unit systems could be suitable for immediate loading in specific scenarios. Further studies are needed to validate these results and investigate the role of implant dimensions and dynamic loading.

When we compare the two-unit dental implant system with the one-unit system, we must clarify some things first. The two-piece system, or the conventional system, is the most common system and consists of two sections. The first section is the implant body itself, which is surgically implanted inside the human bone and acts as an artificial root. The second section, called the abutment, is the section that is connected to the implant body and is outside the gum line and serves as the base for the future crown, bridge, or abutment, or as needed.

Secondly, with regard to the one-unit implant system, it is also called compressive or basal in some cases in another type, and it is integrated between the internal or surgical unit and the external unit in the mouth. It is also called single or monolith or other names, and it has very unique blades for greater stability achieves greater stability by compressing the bone, making it suitable for immediate loading. Therefore, it is called in some types basal because it is sometimes extended to the cortical or basal bone, which is less susceptible to resorption

Two-unit dental implant system

Advantages: First, the high flexibility, as the unit can be easily separated, allowing us to change the angle, direction, or final design of the crown.

This is very important to achieve the desired aesthetics or function, especially in difficult cases where we need to determine the desired angle. Second, the staged method, specifically the two-step surgical method, as when we place the implant inside the bone, we inject and wait a few months before shaping the external piece. This allows for better healing, greater stability in the bone, and better integration, which achieves more reassuring, more aesthetic, and stronger results.

Disadvantages: First, the long treatment period. The two-unit implant system requires a healing period from the beginning of the implantation process until the final replacement. This means a long period that can take several months. Second, it requires more bone mass. Two-unit system implants usually require a higher quantity and quality of bone to ensure successful osseointegration, which requires bone grafting. These are additional, expensive matters that take more time. Third, micro-gap there are sometimes small spaces between the implant and the abutment part, which sometimes causes bacterial accumulation, which in the future affects the success of the implant process.

Dental implants, a one-unit implant system,
Advantages: One surgical stage, since the implant and the outer piece are integrated, we can often make one surgical incision, which simplifies the procedure and reduces the number of appointments. Secondly, immediate loading due to the unique design of the implant blades, which achieves very high stability in the first stage by compressing the bone and engaging with the bone more. This allows us to provide immediate loading, whether temporary or permanent, and sometimes very soon after the surgery. Thirdly, it is suitable for resorption bones. Sometimes, and during bone destructive that is severely resorbed, we cannot make the implant using the two-unit system, while the one-unit or compressive is more suitable. Thirdly, the low cost, sometimes the two-unit system, since it is two pieces, which leads to two sessions, which leads to a higher cost, and therefore the one-unit is sometimes, and most of the time, less expensive. Finally, micro spaces, due to the single design, which is integrated between the outer piece and the implant, there is no gap. Microbial barriers, such as those observed in the two-piece system, reduce bacterial accumulation, which leads to fewer future infections, especially subgingival infections.

Disadvantages: The limited design is because the single piece is a without connector design, so it is difficult to be flexible to adjust to a certain angle, which affects the aesthetics, even if it is sometimes bendable, it does not achieve the required degree. Secondly, the challenge of correcting the angle. In some cases, correcting the angle is a normal challenge. Thirdly, the limited scientific research that guarantees healing for long periods, compared to the two-piece system in dental implants, which contains a lot of scientific research. The single-piece implant system has little scientific research that includes the success of the implant for long periods, so some countries did not give approval, as is the case with the United States MDI system, which did not give permission for the system. The speed of the single-piece supports. Thirdly, the difficulty of lifting the implants in the event of failure of the single-implant system. In the event of failure, the process of lifting it will be a real challenge due to its close connection to the bone. The question now is, which is better, two-piece dental implants or single-piece dental implants? To answer this question, we must determine several points, the most important of which is the quality the patient's bone density: If the bone is sufficient and of good quality, then the two-piece implant system is better to ensure greater success. Secondly, from an aesthetic perspective: If aesthetics are more desired, as is the case with anterior dental implants, then the two-piece implant support system is better. Thirdly, from an aspect of faster healing: If the patient requires less time, then the single-implant system is better, as it has a faster healing process. Fourthly, ease for the technician or doctor: Dentists prefer single implants in terms of comfort and ease of work. Fifthly, cost: It is generally believed that the cost of the single-piece implant system is less than the two-piece implant system.

For all or most cases of conventional implants, the two-unit implant system is considered the gold standard due to its continuous success, high flexibility, ability to achieve greater aesthetics and better functional load, while the single-unit implant system is intended for less severe cases, including patients with little bone, who avoid bone replacement surgery, or in cases that require a short time. In both cases, the patient requires consultation with a dentist specializing in dental implants to determine the best procedure, which includes the condition of the mouth, the bone areas, the purpose of the implant, and the ideal plan for the implant.

Simulation results in SolidWorks show a close relationship between hexagonal and octagonal connector design dental implants within the two-unit system, while the one-unit implant had a significant impact. Despite these results, the length and diameter of the one-unit implant may have influenced the results, as the implant design is primarily designed with a thin, flexible neck. Note that the neck of a one-unit implant is flexible, which is not implemented in the program. We hope for future studies to further explore.

3.CONCLUSION

Results indicate that two-unit systems (hexagonal and octagonal) exhibit superior load-bearing capacity compared to the one-unit system, with the hexagonal design showing marginally better stress distribution. However, differ- ences between hexagonal and octagonal connectors were minimal. The one-unit system displayed higher stress and deformation, potentially due to its thinner, longer design. These findings suggest that connector design significantly influences implant performance, with implications for clinical applications. Future studies should validate these results with experimental data and explore the impact of implant dimensions.

DECLARATIONS

Competing interest

The authors declare that there are no competing interest.

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Ethical Approval

“Not applicable”

Consent for publication

“Not applicable” No funding was received from any financially supporting body

Competing interests

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