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Titanium-Zirconia abutment-implant assemblies: Are they alternatives for single material implants?

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A R T I C L E I N F O

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Implant design
Cemented crowns

A B S T R A C T

Objectives: To compare the biomechanical performance of titanium, zirconia, and titanium-zirconia hybrid abutment-implant assemblies using finite element analysis (FEA).

Methods: Four three-dimensional finite element models of implant-abutment-crown assemblies were developed using Solid Works 2022 SP3.1 and Abaqus 2022 (*Dassault Systèmes*), based on the abutment-implant systems: (1) Titanium abutment and implant - Ti-Ti, (2) Zirconia abutment and implant - ZrO_2-ZrO_2, (3) hybrid - titanium abutment with zirconia implant - Ti-ZrO_2, and (4) hybrid - zirconia abutment with titanium implant - ZrO_2-Ti. A cemented-retained zirconia crown and a 5-mm diameter abutment, with no inclination, were used in all models. The fit between the abutment and the implant was performed by a 9-mm length and 1-mm diameter titanium abutment screw. Volumetric finite elements with a linear tetrahedral shape (C3D4) and "tie" interactions represented 100 % of osteointegration. A distributed load of 200 N was applied to the crown, while the bone was fully constrained. For linear analysis, all materials were assumed to be linear, elastic, isotropic, and homogeneous. The FEA focused on evaluating the stress distribution within the implant, abutment, and surrounding tissues.

Results: The hybrid zirconia-titanium assembly exhibited lower peak stress at the gingiva compared to the titanium-zirconia model and the full titanium or zirconia implant models. The hybrid titanium-zirconia and the full titanium assembly demonstrated the lowest peak stress in the bone, whereas the zirconia-titanium model and the full zirconia implant models exhibited higher stresses. The full titanium and the titanium-zirconia assemblies exhibited the highest stress concentration at the implant-abutment interface, highlighting potential areas for mechanical failure.

Significance: Finite element analysis indicates that the hybrid zirconia-titanium abutment-implant assembly offers a viable alternative to single-material implants. The hybrid configurations combine the advantages of both materials, promoting balanced stress distribution and favourable biomechanical performance. The findings suggests that titanium-zirconia hybrid implants may enhance implant longevity and success rates, making them a promising option for clinical applications.

1. Introduction

Dental implants have revolutionized tooth replacement, by providing both functional and aesthetic solutions for edentulous patients [1–5]. Since their introduction, implants have significantly improved patient quality of life, offering enhanced mastication, phonetics, and aesthetics compared to removable prostheses [6]. The long-term clinical success of dental implants depends on several factors, including osseointegration, biomechanical stability, and biocompatibility with surrounding tissues. Among implant materials, titanium and its alloys have been considered the gold standard for implant materials due to their excellent biocompatibility, corrosion resistance, and mechanical properties. [7,8]. However, despite titanium's well-documented clinical success – demonstrating survival rates exceeding 90 % over several

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decades - concerns have emerged regarding its biological and mechanical limitations have led researchers to explore alternative materials [9,10].

One primary concern is titanium hypersensitivity, which can trigger inflammatory responses in susceptible individuals, potentially leading to peri-implant mucositis and peri-implantitis [9]. Furthermore, titanium implants are prone to corrosion, particularly in the presence of fluoride-containing solutions and acidic oral environments, which may compromise long-term implant stability [8]. Additionally, titanium ion release has been detected in peri-implant soft and hard tissues, raising concerns about potential cytotoxicity, bone resorption, and inflammatory responses [11].

From a biomechanical perspective, titanium exhibits a higher elastic modulus (~110 GPa) than cortical bone (~10–30 GPa), which may lead to stress shielding and bone resorption around the implant [5]. To mitigate these concerns, alternative implant materials have been explored, with zirconia emerging as a promising candidate [12]. Zirconia is a ceramic material that has gained increasing attention due to its lower bacterial adhesion and remarkable mechanical properties [7]. From a mechanical standpoint, zirconia has a higher hardness, a higher modulus, typically ranging from 200 to 210 GPa [13], and wear resistance higher than titanium, making it less susceptible to surface degradation, which may influence its interaction with bone tissue and impact implant integration. Recent clinical trials have highlighted its potential benefits [11]. However, its brittle nature and lower fracture toughness raise concerns regarding long-term mechanical reliability, particularly under dynamic occlusal forces [1]. Moreover, zirconia implants have demonstrated mixed results regarding osseointegration, with some studies suggesting slower bone healing compared to titanium [11].

Despite these advantages, zirconia does not exhibit clear superiority over titanium in terms of osseointegration, mechanical strength, or long-term durability. Consequently, some authors continue to regard titanium as the preferred material for dental implants [12,14]. To optimise implant performance, recent innovations have focused on combining zirconia and titanium within implant systems to capitalise on the strengths of both materials [15]. Researchers have investigated the biological effects of these hybrid systems, assessing parameters such as survival rates, bleeding on probing, marginal bone loss, and pocket depth. The findings suggest that implants incorporating zirconia abutments with titanium implants yield superior outcomes. Specifically, zirconia abutments exhibit enhanced compatibility with soft tissues, while titanium implants provide optimal osseointegration [16].

In contrast, a study conducted by Elias, Fernandes & De Biasi, in 2017, examined the compressive and fatigue strength of titanium-zirconia hybrid implants. The results indicated promising mechanical performance; however, further research is necessary to comprehensively evaluate their mechanical properties [15]. To date, only a limited number of studies have investigated the mechanical behaviour of these hybrid systems [17–19], with most focusing solely on compression strength and fatigue resistance. Notably, key aspects such as load transfer, displacement, and tensile stress distribution at the implant interfaces on surrounding tissues remain underexplored.

Finite element analysis (FEA) has become a fundamental tool in implantology and prosthetic dentistry, allowing researchers to study the mechanical behaviour of dental implants and surrounding tissues under various loading conditions. Unlike in vivo and in vitro methods, which are often constrained by ethical, biological, and material limitations, FEA provides a non-invasive, highly detailed numerical simulation of stress distribution, strain, and deformation within complex structures. This computational technique enables the evaluation of implant performance, longevity, and failure risks under clinically relevant conditions, thereby guiding implant design improvements [18,20].

One of the key advantages of FEA in dental implant research is its ability to assess the impact of material selection, implant geometry, and prosthetic design on mechanical performance. For instance, Soares *et al.* (2021) used FEA to investigate the load-bearing capacity of ceramic restorations supported by different implant foundations (PEEK vs. zirconia), concluding that a more rigid foundation enhances restoration longevity by reducing tensile stress concentration. Their findings reinforce the importance of selecting implant materials with optimal biomechanical properties to prevent mechanical failures [21].

The finite element method has been instrumental in analysing the biomechanics of hybrid implant systems, such as zirconia abutment-titanium implant combinations. These systems aim to maximize material advantages, with zirconia improving soft tissue compatibility and titanium enhancing bone integration. Lee *et al.* (2021) used FEA to study implant diameter, connection type, and microgap effects on fatigue failure, concluding that soft tissue-level implants offer better mechanical stability [22]. However, stress transfer and fatigue resistance at the abutment-implant interface require further research.

To address this gap, the present study aimed to evaluate the biomechanical performance of titanium, zirconia, and hybrid abutment-implant assemblies using finite element analysis (FEA). Specifically, we analyse stress distribution in hard and soft tissues, load transfer, and potential failure points. By assessing these factors, we seek to determine whether zirconia-titanium hybrid implants provide superior biomechanical outcomes compared to titanium abutment and implant or zirconia abutment and implant systems. The findings of this study may contribute to optimizing implant design and improving clinical decision-making for long-term implant success.

2. Material and methods

2.1. Image acquisition by micro-CT scanning

A three-dimensional finite element analysis (FEA) model of a mandibular posterior crown-implant-bone assembly was constructed to evaluate stress distribution and biomechanical performance. A sound second left mandibular molar (mesiodistal length is 10.5 mm and the buccolingual length was 9.15 mm) from the University of Leeds digital laboratory tissue bank was scanned using micro-CT imaging (NEOSCAN, XYZ Ltd., UK) (Figs. 1 and 2). The equipment was adjusted to scan the whole tooth, with a beam accelerating voltage of 102 kV and X-ray beam current of 96 A. Initially, tag image file format (TIFF) 16-bit images, were obtained (Fig. 2 – B). Using NRecon® software (Version 1.7.4.2, Bruker; Aartselaar, Belgium), the region of interesting was then selected to generate horizontal layers of the inner structure of the tooth (transversal slices). Nonadjacent bitmap slices were then used for the reconstruction process to generate the 3D-FE model-creation, with an equal separation distance of approximately 0.152 mm. A segmentation process was then used to generate the volumes (binary) for the enamel, dentine, and pulp, generating a mesh of the entire image volume using triangulated 2D shell-elements (STL-stereolithography) (Fig. 2-C). Only the crown geometry was used and refined using Autodesk Meshmixer v. 3.5.474 (Austodesk, Inc. CA, USA) and adjusted with Autodesk Fusion 2.0.19426 × 86_64 (Austodesk, Inc. CA, USA) to fit the abutment.

2.2. Finite element modelling

2.2.1. Geometry and meshing parameters

A three-dimensional finite element master model of implant-abutment-crown assemblies was designed using SolidWorks 2022 SP3.1 (Dassault Systèmes SolidWorks Corporation and MA, US) (Fig. 3) and Abaqus/CAE 2022 software (Dassault Systèmes Simulia Corporation and MA, US), consisted of nine components added to the model to accurately mimic an actual clinical implant treatment: crown, cement, cotton (sealing), abutment, abutment screw, implant, gingiva, cortical bone, and cancellous bone. A cemented-retained zirconia crown and a 5-mm diameter abutment, with no inclination, were used in all models. The abutment design was symmetrical, integrating cylindrical and conical sections for optimal load distribution as the middle section was curved, forming a bell-like contour. The fit between the abutment and

Fig. 1. Dimensions of the crown mesiodistally and buccolingually.

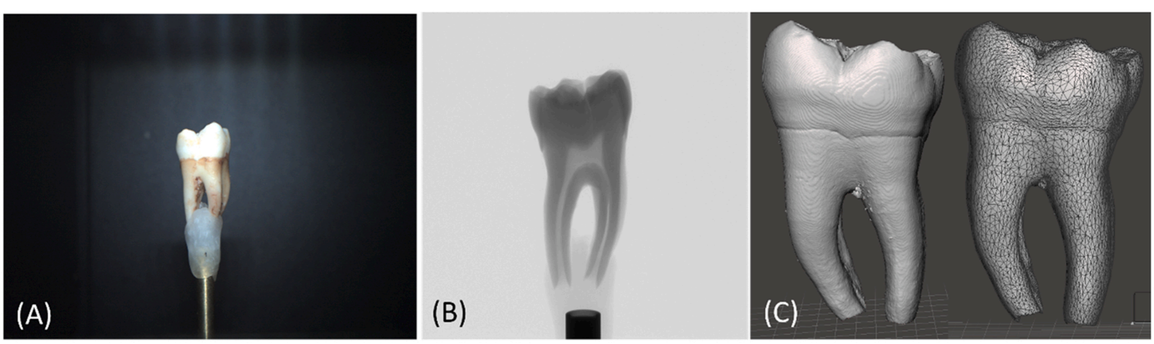

Fig. 2. (A) Representation of the tooth inside the NEOSCAN machine (B) An image of the full tooth (C). On the left the scanned tooth in Meshmixer, on the right represent the tooth with mesh.

the implant was performed by a 9-mm length and 1-mm diameter titanium abutment screw. The thickness of the threads is 0.6 mm with a patch of 0.8 mm. The implant geometry was inspired from BioHorizons's tapered PTG implants (BioHorizons, AL, USA).

The implant dimensions were 15 mm in length and 5 mm in diameter. For the soft tissue, to mimic the ideal gingiva thickness in the posterior mandibular region, less than 2 mm [23], the gingiva was set to 1.5 mm, and 10 mm in length. For the cortical bone, the length and thickness were set to 10 mm and 2 mm respectively. Regarding the cancellous bone, the length is similar to cortical bone, 10 mm in length, and for the thickness was set to 32.3 mm, to accurately evaluate the stress distribution resulting from the implant assembly. From the master model, four configurations were analysed, based on the abutment-implant systems: (1) Titanium abutment and implant - Ti-Ti, (2) Zirconia abutment and implant - ZrO_2-ZrO_2, (3) hybrid - titanium abutment with zirconia implant - Ti-ZrO_2, and (4) hybrid - zirconia abutment with titanium implant - ZrO_2-Ti.

Each part was meshed using linear tetrahedral elements (C3D4) optimized for computational efficiency (Table 1 and Fig. 4).

2.2.2. Boundary conditions

A 200N-load was applied vertically to the crown using a stainless-steel semi-sphere (9.5 mm diameter), to simulate chewing forces [24]. All parts were "tie" constrained to represent ideal osseointegration and the optimal soft tissue conditions. Moreover, the coefficient friction between the abutment and abutment screw and implant with the surrounding tissue was set to 0.3 [25]. The bone was fully constrained in the X, Y, and Z directions, representing the immobility of the jawbone within the skull Fig. 4-B.

2.2.3. Material properties

The materials were considered linear, elastic (the deformation or displacement of the structure is proportional to the applied force and independent of the amount of displacement), isotropic (material properties and mechanical behaviour are the same in the three directions of X, Y and Z), and homogeneous (the mechanical properties of the

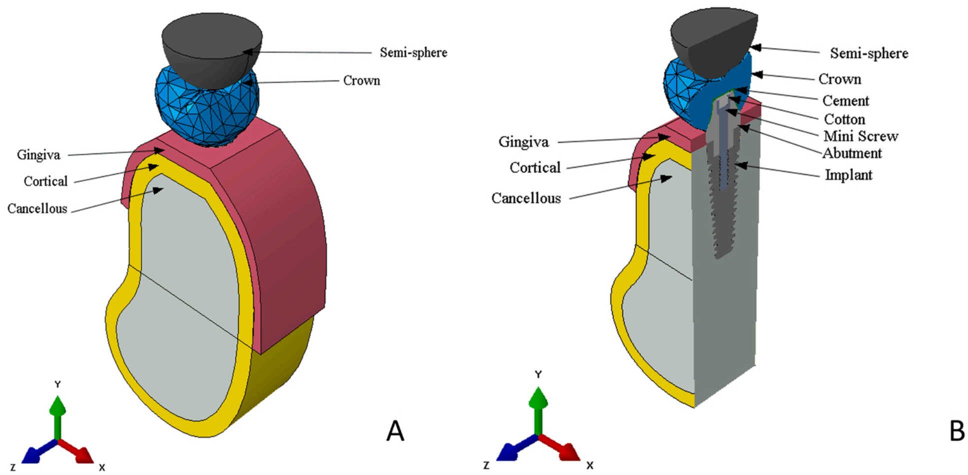

Fig. 3. – (A) Full assembly of the model, (B) Parts of the model.

Table 1
Nodes, elements, and mesh size of the finite element models.

Components	Nodes	Elements	Mesh size
Semi-sphere	263	1026	1.3
Crown	20,423	109,164	0.28
Cement	1805	5271	0.3
Cotton (sealing)	380	1450	0.23
Abutment	4358	20,181	0.29
Abutment screw	4167	18,426	0.23
Implant	3036	12,585	0.66
Gingiva	1430	5184	0.93
Cortical bone	1181	4170	1.6
Cancellous bone	2530	11,743	1.6

material are uniform) [26]. These assumptions are commonly made in biomechanical FEA to simplify the analysis while still providing useful insights into stress distributions. The input parameters were the Young's modulus and Poisson's ratios of the nine-part model, as shown in Table 2.

2.2.4. *Analysis type and criteria*

For the linear analysis, increments are necessary to run each model and can be done by Abaqus default algorithms. However, for these models, we had to manually set-up fifteen increments to ensure a smooth and accurate representation of the load application and stress distributions. The FEA evaluated the stress distribution within the implant, abutment, and surrounding tissue by using Abaqus/CAE software. Coloured fringes graphs were used to identify the maximum peak stresses for all failure criteria These graphs provide a visual representation of the stress distribution, allowing for easy identification of areas of high stress that could potentially lead to implant failure. By using Abaqus/CAE the outcome results were for displacement and von Mises stress (tensile, compression and shear) in (MPa), maximum principal stress (tensile) in (MPa) in addition to maximum principal strain (deformation).

3. Results

The stress-patterns in the crown-implant-bone models exhibited three-dimensional distributions. Stress concentrations observed primarily at the load application site and near the abutment-implant interface in all simulated models. Fig. 5 and Table 3 summarise the peak displacements (mm) for each model.

The results showed that, in terms of displacement, after applying 200 N load, the ZrO_2- ZrO_2 assembly exhibited the least displacement. On the other hand, the full titanium model demonstrated the highest displacement.

Figs. 6 and 15 show von Mises stresses (MPa) and the maximum principal stresses (MPa) for all models respectively. In addition, Tables 4 and 5 show the peak stresses for each model.

The von Mises stress results in Fig. 6 showed that there is more stress on the abutment screw components when the abutment was made from titanium. Meanwhile, the result demonstrated that the stress was lower

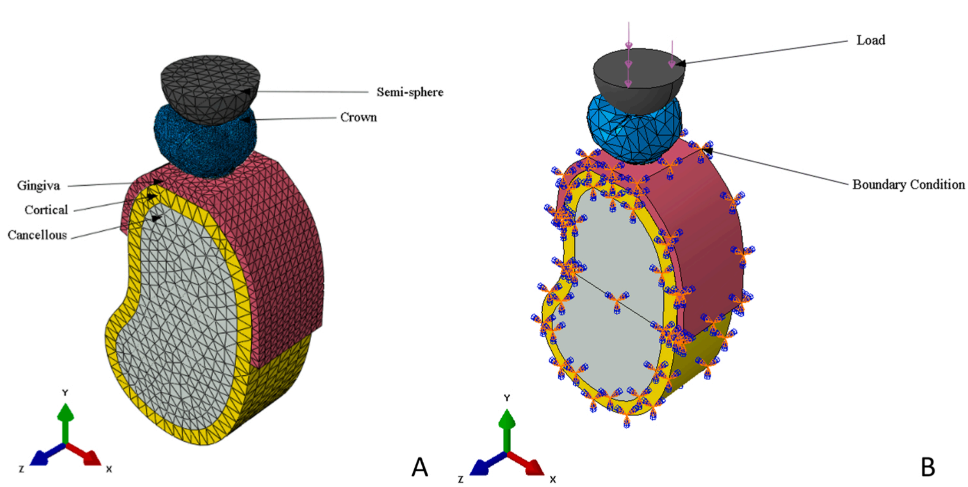

Fig. 4. (A) Finite element model (B) model with “tie” constrains and boundary conditions.

Table 2 –
Young's modulus (GPa) and Poisson's ratios all simulated materials.

Material	Young's modulus (GPa)	Poisson's ratio	Reference
Titanium (abutment/ implant)	110	0.3	[13]
Zirconia (abutment/ implant)	210	0.25	[13]
Zirconium-Crown	210	0.3	[27]
Stainless steel	210	0.33	[28]
Gingiva	0.01	0.4	[29]
Cotton (sealing) 0.3-mm	2.4	0.4	[30]
Cement (resin-based) 0.2 mm thickness	7.0	0.24	[16]
Cancellous bone	1	0.3	[13]
Cortical bone	15	0.3	[13]

when the abutment was composed of zirconia. The lowest peaks were presented by zirconia abutment, and the highest when Ti was the abutment (Table 4).

In the context of maximum principal stress (MPa) for the full dental implant assembly, the results showed that the full zirconia assembly (implant and abutment) exhibited more tensile stress in the region of the crown-abutment interface, while the full titanium assembly exhibited lower tensile stress at the same region. In terms of compressive stress (minimum principal stress), all four models showed almost similar results on the abutment screw implant interface. The lowest peaks were presented by zirconia abutment and the titanium implant, and the highest when it was full ZrO_2- ZrO_2 assembly (Table 4).

Regarding the implant assembly, abutment, abutment screw and implant, von Mises stresses were summarised in Figs. 8, 9, and 10, respectively.

Regarding the abutment, as shown in Fig. 8 above, ZrO_2-Ti implant assembly exhibited the highest stress when compared with all other assemblies, especially on implant abutment interface. Whereas Ti-ZrO_2 showed the least stress on the implant abutment interface. Moreover, the results showed that zirconia abutment demonstrated higher stress on the crown abutment interface when compared to Ti abutment. Furthermore, regarding the abutment screw the results from the von Mises test showed that abutment screw was subjected to more stress in Ti-Ti combination, as it shows in Fig. 9. Regardless of the material of the implant. The abutment screw exhibited more stress on the on the abutment screw interface when the abutment is made from Ti comparing to zirconia abutment. In terms of implant, the results demonstrated that ZrO_2- ZrO_2 combination had the highest peak stress when compared with the three other combinations as it is shown in Table 5. Fig. 10 shows that the abutment-implant interface had more stress when the implant is made from zirconia than titanium regardless of the material of the abutment.

Table 3
Peak displacement (mm) for all models, based on the abutment-implant systems.

Models	Ti-Ti	ZrO_2- ZrO_2	Ti-ZrO_2	ZrO_2-Ti
Displacement	1.497E−03	1.300E−03	1.378E−03	1.414E−03

For the maximum principal stress on the implant assembly, abutment and abutment screw as well as the implant is shown in Figs. 11, 12, and 13, respectively.

In term of maximum principal stress, Fig. 11 and Table 5 demonstrated that ZrO_2-Ti had the most tensile stress on the abutment implant interface. Looking at same interface, ZrO_2- ZrO_2 combination followed by Ti-Ti combination demonstrated lesser tensile stress than ZrO_2-Ti. While Ti- ZrO_2 showed the least stress on abutment implant interface.

Regarding the abutment screw, the maximum principal stress result showed that Ti-Ti configuration had the peak stress value while ZrO_2-ZrO_2 combination exhibited minimum peak stress compared with all models, as it is shown in Fig. 12. In terms of the implant, the result showed that highest stress concentration is when the implant is made of zirconia regardless of the abutment material, where Ti- ZrO_2 combination showed the highest peak stress when compared with all three models, followed by ZrO_2- ZrO_2 configuration.

Regarding the gingiva, the maximum principal strain and the interaction between the implant and soft tissue is demonstrated in Fig. 14 and Table 6.

The results of maximum principal strain showed the deformation in all four models. The result demonstrated that Ti-Ti combination had the highest deformation when compared to all models, followed by ZrO_2-ZrO_2, and Ti- ZrO_2 combination, while ZrO_2-Ti had the lowest deformation rate among all models.

The maximum principal strain, the peak strain was shown in the cortical and cancellous bone shown in Fig. 15.

The results of the maximum principal strain of the bone showed that the full titanium had the highest deformation peak when compared to all other combinations as it is shown in Fig. 15. Nevertheless, when examining the result from Table 6, ZrO_2 implant exhibited higher strain deformation when compared to Ti implant, and these results were for both cortical and cancellous bone.

The results of the maximum peak stresses and strain and the displacement for the other parts of the models are presented in Annex 1.

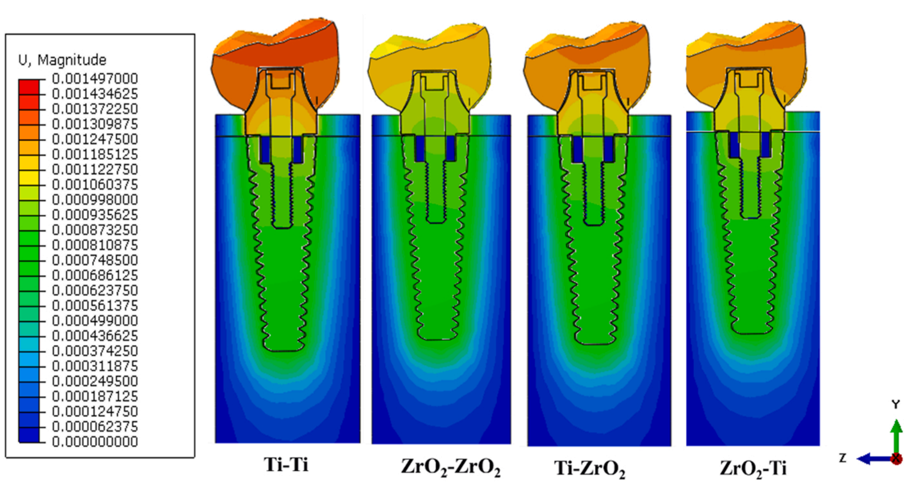

Fig. 5. Displacement (mm) of the full structure for each model, based on the abutment-implant systems. The maximum value was found at the zirconia crown, where the load was applied.

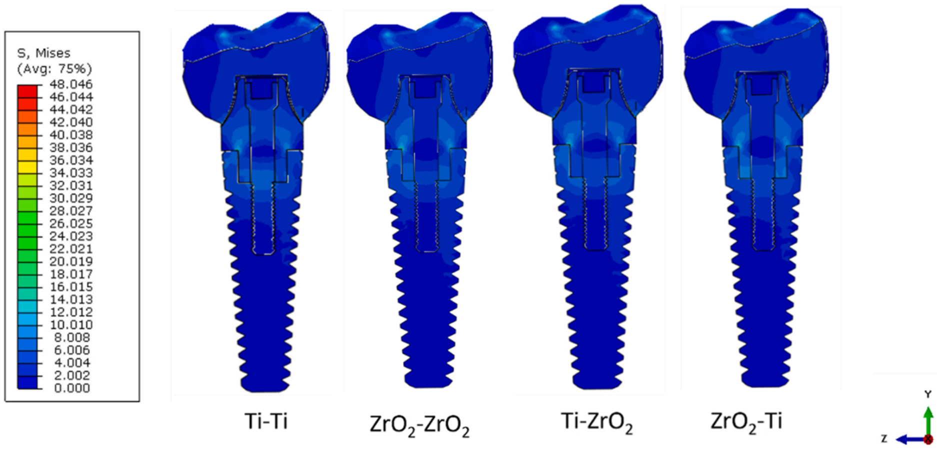

Fig. 6. von Mises stress (MPa) of the full dental implant assembly for each model, based on the abutment-implant systems. The maximum value was found at the sharp angles at the abutment-implant interfaces.

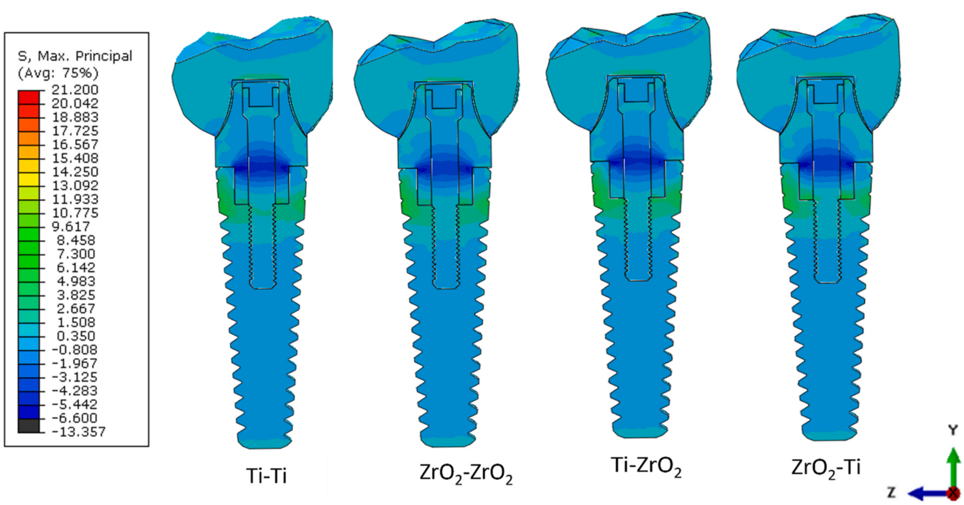

Fig. 7. Maximum principal stress (MPa) of the full dental implant assembly for each model, based on the abutment-implant systems. The maximum value was found at the interface implant collar, just below the implant abutment interface.

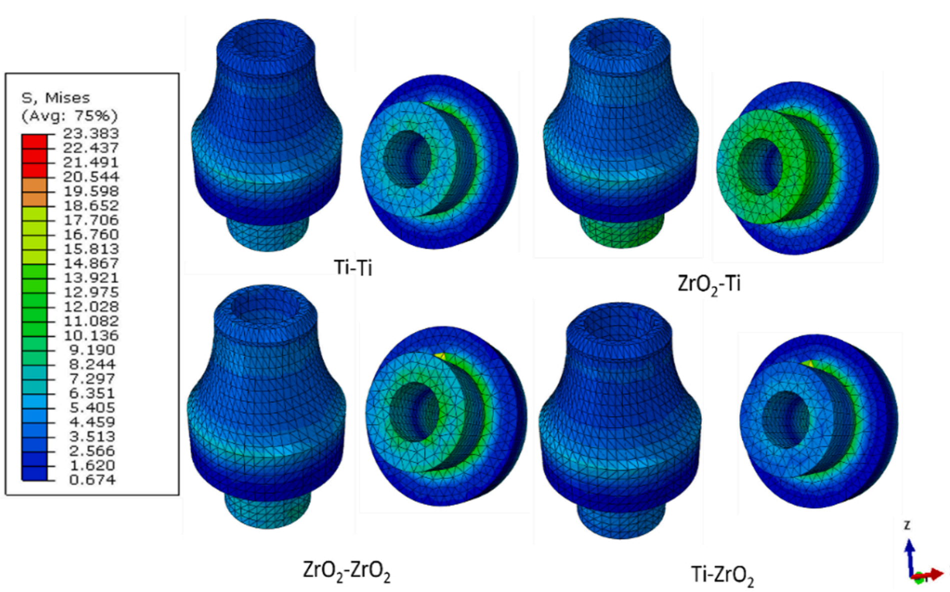

Fig. 8. von Mises stress (MPa) of the abutment for each model, based on the abutment-implant systems. The maximum value was found at the abutment-implant interfaces, particularly at the sharper 90° angle.

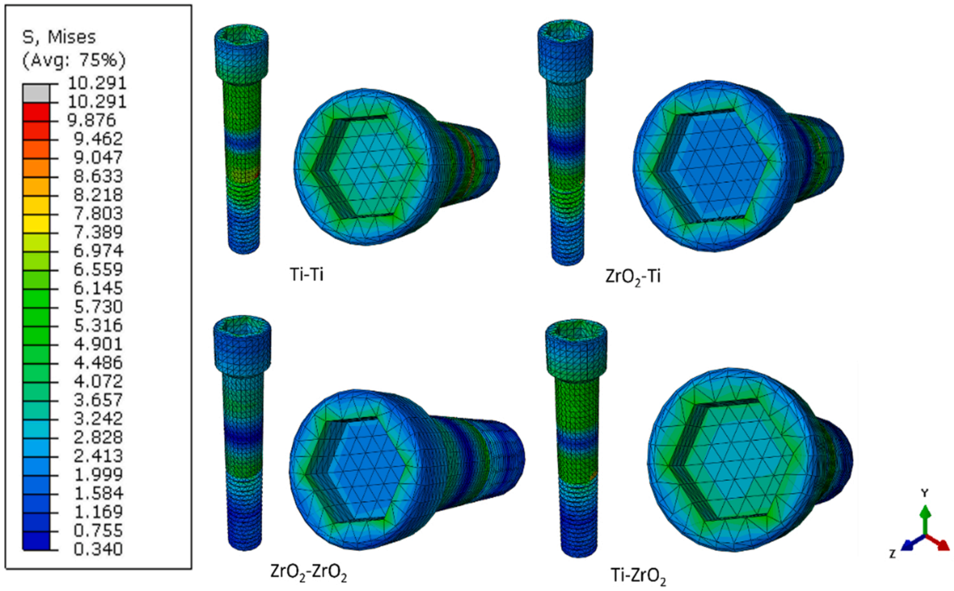

Fig. 9. von Mises stress (MPa) of the abutment screw for each model. based on the abutment-implant systems. The maximum value was found at the junction between the smooth part of the abutment screw (shank) and the threads, correspondent to the implant collar.

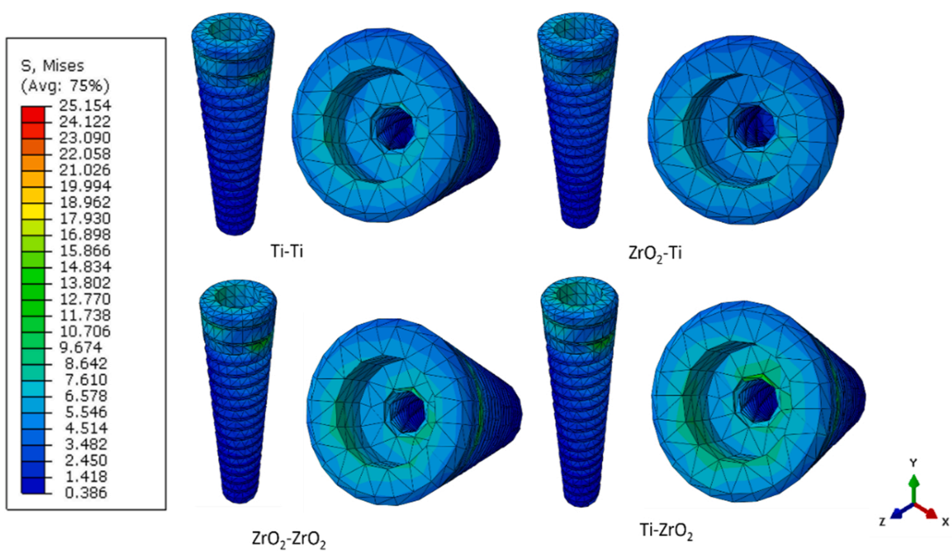

Fig. 10. von Mises stress (MPa) of the implant for each model, based on the abutment-implant systems. The maximum value was found at the abutment-implant interfaces.

The colour fringe graphs for all parts are stored at the University of Leeds finite element files repository, and it is available upon request.

4. Discussion

The success of dental implants treatment depends on two key factors: (1) biological factors, such as bone quality and quantity, patient oral health, and soft tissue condition, and (2) biomechanical properties of the implant components. In this study, we investigated the biomechanical performance of zirconia and titanium implant abutments and implants combinations, by using finite element analysis (FEA). Displacement, von Mises stress, maximum principal stress and maximum principal strain were used as failure criteria to assess the strain, tensile, and the deformation in the implant components and surrounding tissues.

Before discussing our results, some limitations must be acknowledged to avoid misinterpretation: (i) the 3D FEA model does not fully replicate the complex multidirectional loading conditions present in the oral cavity, as a vertical load (pressure) was applied using a sphere following the normal occlusion distribution, as is a common approach used to simulate occlusal forces and distribute them uniformly onto the crown contact points [5,26,35]; (ii) the bone and soft tissue were modelled as healthy and homogeneous, which does not reflect the variability of clinical conditions, as the focus was on the materials choice; (iii) complete osseointegration was assumed, which might vary clinically; (iv) Regarding the crown, based on the literature review and for this research, cement retained zirconia crown was the ideal choice, to accurately evaluate the biomechanical properties of combining both titanium and zirconia abutment-implant assemblies, however, in some countries, the screw-retained is still the most used implant system; also regarding the cement, glass ionomer cements are not commonly used for cementation of implant crowns, implant crowns are usually cemented with zinc polycarboxylate cements or more commonly resin based cements, it would be useful to consider that in future work; (v) cotton was used as the screw access hole sealing material instead of

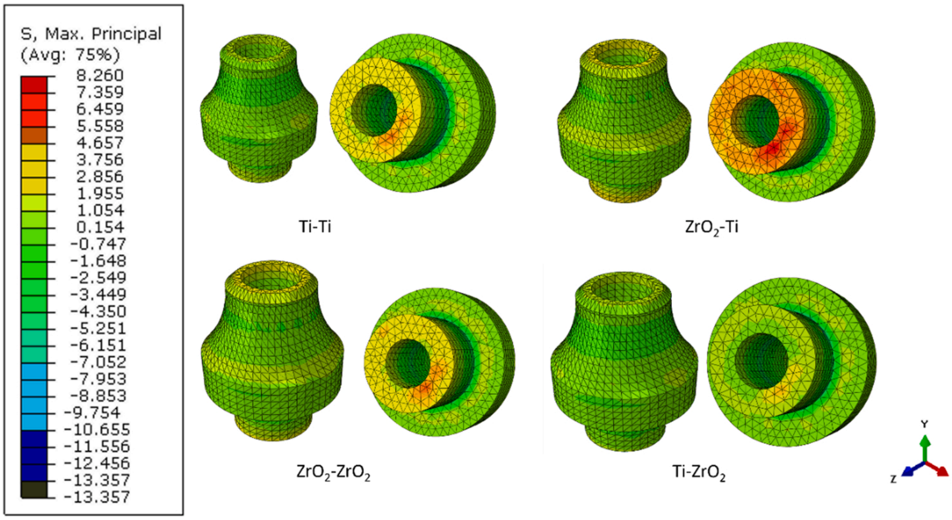

Fig. 11. Maximum principal stress (MPa) of the abutment for each model, based on the abutment-implant systems.

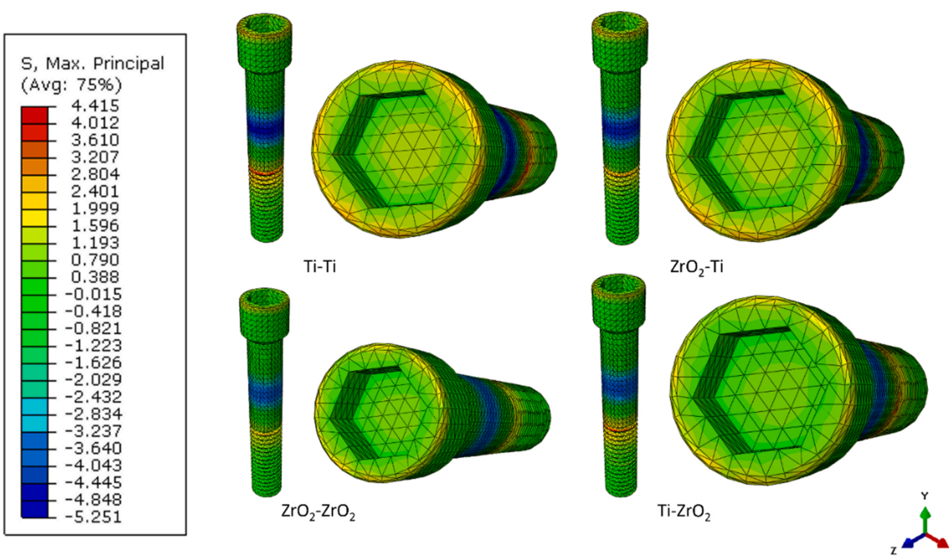

Fig. 12. Maximum principal stress (MPa) of the abutment screw for each model, based on the abutment-implant systems.

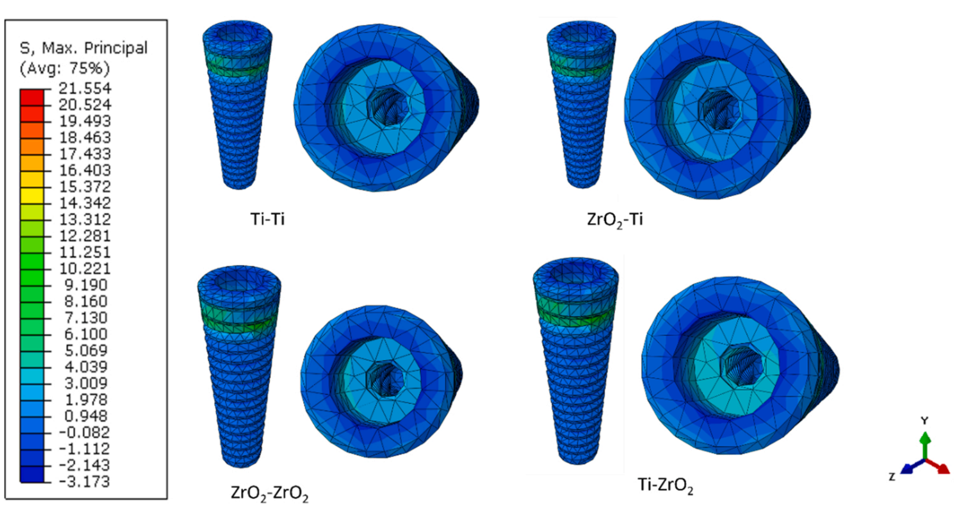

Fig. 13. Maximum principal stress (MPa) of the implant for each model, based on the abutment-implant systems.

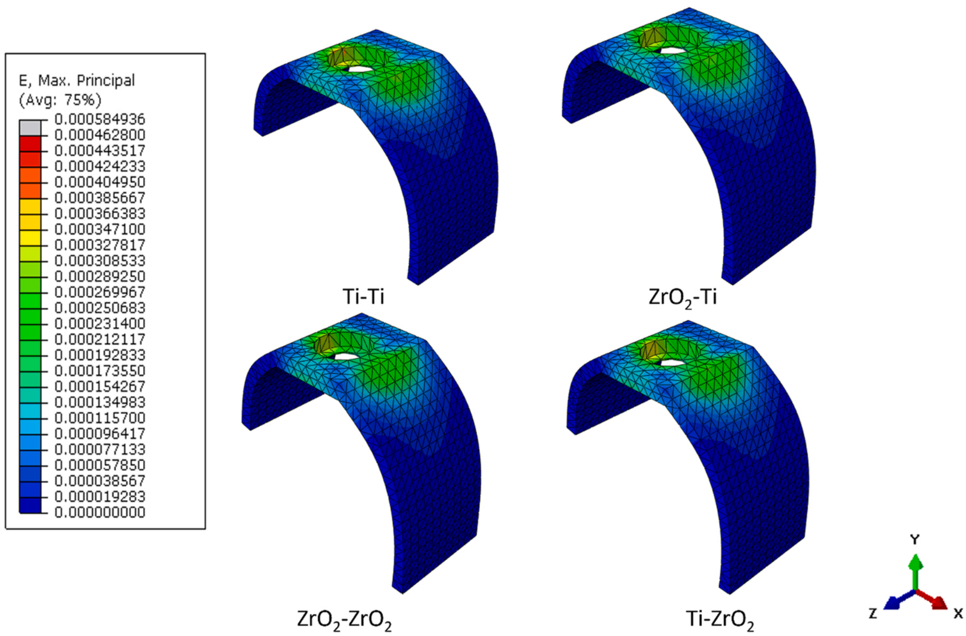

Fig. 14. Maximum principal strain on the gingiva, based on the abutment-implant systems.

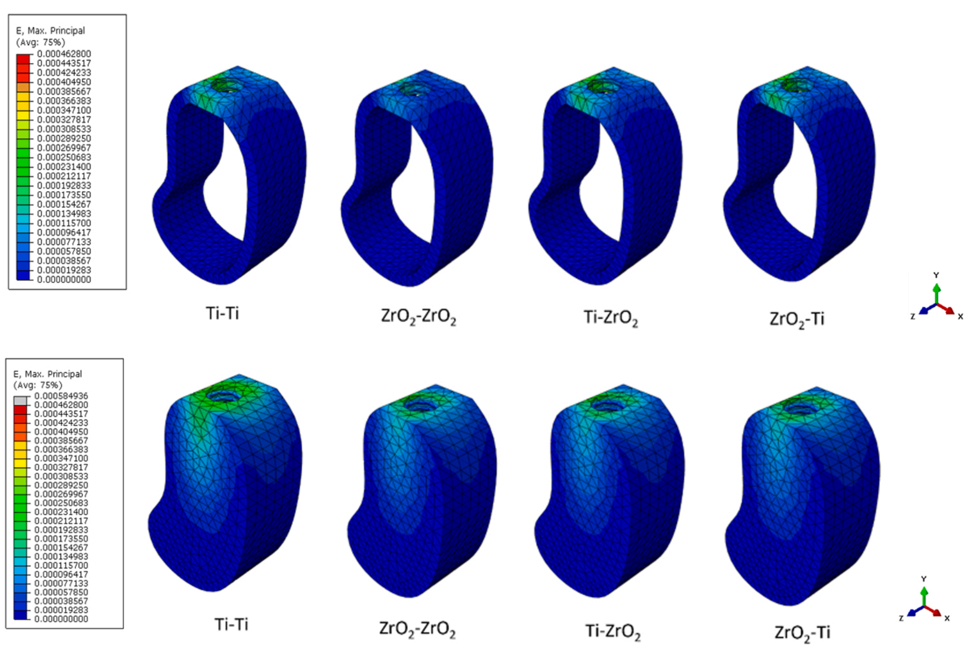

Fig. 15. Maximum principal strain of cortical and cancellous bone, based on the abutment-implant systems.

Table 4
von Mises peak stresses (MPa) and maximum principal peak stress for all models, based on the abutment-implant systems.

Models	Ti-Ti	ZrO_2- ZrO_2	Ti-ZrO_2	ZrO_2-Ti
Von Mises peak stress	47.820	45.271	48.046	45.153
Maximum principal peak stress	18.036	21.393	21.554	17.729

polytetrafluoroethylene (PTFE) tape, which could be a more suitable option due to its lower elastic modulus, better sealing properties, and reduced bacterial adhesion. However, while PTFE is typically applied in thinner layers and may improve soft tissue response, its impact on the overall biomechanical behaviour of the implant system is expected to be

Table 5
von Mises and maximum principal peak stress (MPa) for all three-implant part for all models, based on the abutment-implant systems.

Models	Ti-Ti	ZrO_2-ZrO_2	Ti-ZrO_2	ZrO_2-Ti
Abutment von Mises	20.434	23.275	20.486	23.383
Abutment screw von Mises	10.291	9.406	8.796	8.568
Implant von Mises	19.845	25.154	25.123	19.941
Abutment maximum principal stress	6.981	6.819	7.695	8.260
Abutment screw maximum principal stress	4.415	2.832	3.068	4.006
Implant maximum principal stress	18.036	21.393	21.554	17.714

Table 6
Maximum principal peak strain of the gingiva and the bones.

Models	Ti-Ti	ZrO_2-ZrO_2	Ti-ZrO_2	ZrO_2-Ti
Gingiva	7.223E−04	7.192E−04	6.291E−04	5.938E−04
Cortical bone	4.525E−04	4.628E−04	4.619E−04	4.542E−04
Cancellous bone	5.849E−04	6.101E−04	6.091E−04	5.871E−04

minimal. The use of cotton in this study is justified as it provides higher stress transmission to the implant and surrounding bone while contributing to greater overall structural integrity due to its higher stiffness. Additionally, cotton's widespread clinical use and well-documented mechanical properties make it a relevant choice for FEA simulations; (vi) this study was conducted under static load, therefore a further study under dynamic load is needed [26].

The results of displacement for the full implant assembly in Fig. 5 and Table 3 shows that Ti-Ti combination exhibit the highest displacement, followed by Ti-ZrO_2 then ZrO_2-Ti, with ZrO_2- ZrO_2 implant showing the lowest displacement. This pattern is consistent with the elastic modulus of the materials; titanium, with a lower modulus compared to zirconia, is more prone to deformation. These findings highlight zirconia abutment́s mechanical advantage in reducing displacement within the implant system. Similar findings were reported by Mitra *et al.* (2023), who highlighted that implant material stiffness plays a crucial role in controlling displacement and stress transmission [4]. Furthermore, factors such as implant diameter, length, and occlusal loading angle also influence displacement [3,17,31–33] are additional factors. Overall, the lower the elastic modulus of the materials used in the system, the higher the displacement and therefore the deformation.

In regard to the full implant assembly, von Mises stress (Fig. 6 and Table 4) shows that Ti-ZrO_2 had the highest stress followed by Ti-Ti, ZrO_2-ZrO_2 and ZrO_2-Ti. The stress is more concentrated at the abutment-implant interface in all models (Fig. 14). The stress is higher on the ZrO_2 abutment than Ti abutment. However, the results demonstrate that zirconia abutment transmit less stress to the other parts of the implant, such as the abutment screw and the implant when compared to the Ti abutment, which, at the end, can be more beneficial clinically. This reinforces findings by Al-Zordk *et al.* (2020), who observed that zirconia abutments transmit less stress to adjacent implant components [34] Moreover, Shen *et al.* (2024) reported that implant-abutment screw diameter significantly impacts stress distribution, an aspect that should be considered in future designs [5].

Maximum principal stress analysis (Fig. 7 and Table 4) shows that the zirconia abutment presented more tensile stress then the Ti, especially on the crown-abutment interface. Moreover, the zirconia implant shows more stress than Ti implant at the abutment-implant interface. Table 4 demonstrated that zirconia implant had higher stress in all combinations than Ti implant, while the abutment screw had no significant different in all four models. The maximum principal stress criterion is important because it shows where the highest probability of fracture is, thus it is expected that the abutment has more chances to be lost than the whole implant, allowing the clinicians to replace it, if necessary. On the other hand, as this stress concentration is due to the shape of the abutment rather than the elastic properties of the material, new abutment designs should be developed as an improvement of these systems. This finding aligns with Yesilyurt & Tuncdemir (2021), who found that zirconia-based hybrid abutments were more prone to tensile stress compared to titanium-based designs [35]. Importantly, our results suggest that new abutment designs should be developed to optimize stress distribution, a point also emphasized by Poovarodom *et al.* (2024) [36]. This distribution may reduce mechanical fatigue and prolong the lifespan of surrounding parts, including the abutment screw and implant.

When each part is separately evaluated, the von Mises stress on ZrO_2-Ti combination on the abutment implant interface was higher (Fig. 8), showing that the ZrO_2 abutment had transmitted less stress to both abutment screw and implant than the other scenarios. Concerning the abutment screw, Ti-Ti combination abutment screw had the highest stress as it shown in Fig. 9, and the lowest von Mises stress was presented by the ZrO_2- Ti combination. The reason for this result can be traced back to the abutment, since zirconia abutment transmitted less stress to the adjacent parts that abutment screw had lower stress concentration. Nevertheless, the ideal implant in term of abutment screw stress remains to be Ti. Titanium as abutment have shown more stress transmission to the neighbouring parts but, as an implant, it shows the ideal mechanical properties and more stable with other implant components. Moreover, regarding the von Mises stress on the implant, Figure 18 shows that Ti implant has lower stress when paired with zirconia abutment. Ti, on the other hand, shows better results than zirconia as implant in terms of stress distribution to the surrounding tissue.

In terms of maximum principal stress in each part, the results showed that ZrO_2-Ti has the highest tensile stress on the abutment implant interface, and that is the case for all the zirconia abutments, while titanium abutment had the lower tensile stress (Fig. 11). Regarding the abutment screw, we can conclude that Ti abutment had more stress on the abutment screw than zirconia abutment (Fig. 12). Regarding the implant, Fig. 13 shows that Ti implant exhibits less stress regardless of the abutment material, which reinforces that it is less to fail mechanically than zirconia implants, regardless of the materials of the abutment.

Concerning the maximum principal strain of the gingiva, the results showed that the peak strain was in Ti-Ti combination, that could be traced back to the displacement, since Ti- Ti combination had the largest displacement, thus it also produced the higher deformation of the gingiva when compared to the other models (Fig. 14). Moreover, both ZrO_2-ZrO_2 and Ti- ZrO_2 had higher deformation than ZrO_2-Ti. The ZrO_2-Ti showed the lowest deformation than all models. This finding brings up a question, in terms of deformation of the soft tissue: "is zirconia better than titanium?" (for the abutment and to avoid the deformation of the soft tissues). Mechanically speaking, for the configuration we used in this study, we can answer "yes, it is". ZrO_2- ZrO_2 implant assembly had the second highest value after Ti-Ti combination, thus, based on the results, zirconia abutment is ideal for the soft tissue only when is paired with titanium implant. The results of the maximum principal strain of the bone (Table 6) demonstrated that full titanium have the highest peak deformation. Nevertheless, when taking a closer look at each part separately, we can see that the lowest deformation was found when Ti was used as an implant.

In terms of the gingiva, displacement had a huge impact on the soft tissue as well as the stiffness of these material. Titanium is less stiff than zirconia, with a Young's modulus of zirconia being practically double that of a titanium implant [33], which shows more deformation of the surrounding tissue. Following that statement, Ti-Ti had the poorest finding among all models in terms of deformation, nevertheless comparing both ZrO_2-Ti and Ti-ZrO_2 combinations, the results showed that titanium abutment had higher deformation than zirconia, mechanically favouring the soft tissue. However, in terms of the bone, the result was the opposite. The deformation of both cortical and cancellous bone was higher in zirconia implant, which means that the optimal treatment option in terms of bone interaction remains titanium.

Regarding prosthetic considerations, FEA has been widely used to compare screw-retained vs. cement-retained restorations. Lee *et al.* (2021) found that screw-retained crowns showed superior stress distribution [16], though Cicciu *et al.* (2014) and Ragauskaitė *et al.* (2017) reported that cement-retained crowns offer better (more homogeneous) occlusal force dissipation but pose higher biological risks, such as peri-implant soft tissue inflammation or pathological bone resorption [18,19]. Moreover, these last authors [18] reported in their literature review that screw-retained crowns demonstrated more failures such as porcelain cracks and fractures or screw loosening. These findings emphasize the need to refine hybrid implant designs, balancing zirconia's mechanical efficiency with biological compatibility.

In summary, high stress was found at the abutment-implant interface, which is a key factor to reflect on as it is a critical interface where bacterial invasion can occur resulting in gingival inflammation which will results in biological complications leading to bone loss, this will need to be investigated/looked into in further details. This finding aligns with Demachkia *et al.* (2022), who used finite element analysis (FEA) and digital image correlation to demonstrate that hybrid abutments, specifically zirconia mesostructures cemented to titanium bases, influenced stress distribution and deformation in implant-supported prostheses [37]. In their study, the higher deformation was found in the cervical region with a higher magnitude for the angled hybrid abutment, which highlights that more factors, such as the abutment design, should be improved to be positioned axially, whenever possible, according to these authors.

Zirconia abutment demonstrates superior mechanical behaviour in minimizing displacement and stress transmission, making it an ideal material for abutments, in terms of soft tissue mechanics, in special deformation. However, its use as a implant may increase deformation in the surrounding bone, potentially compromising long-term osseointegration. Studies by Choi *et al.* (2021) [26] highlight the clinical implications of implant-abutment material selection on gingival adaptation, emphasizing that the mechanical properties of the implant-abutment interface influence peri-implant tissue responses, reinforcing our findings that zirconia abutments reduce gingival deformation, while maintaining stability. Furthermore, FEA studies by Poovarodom *et al.* (2024) [36], Kim *et al.* (2019) [8], and Sakar *et al.* (2023) [38] demonstrate that abutment configuration significantly impacts stress distribution, showing that modifying the abutment taper and gingival height significantly influences bone remodelling, indicating that micromovements at the connection site can influence soft tissue adaptation, and demonstrating that abutment material selection plays a crucial role in minimizing stress at the implant neck and surrounding tissues, respectively. Al-Zordk *et al.* (2020) [34] investigated hybrid abutment-crowns and found that zirconia abutments exhibited superior mechanical stability, particularly in torque maintenance and fracture resistance after thermal aging. This finding is consistent with ours that zirconia abutments, when paired with titanium implants, lead to better soft tissue mechanical behaviour than ZrO_2-ZrO_2 or Ti-Ti system configurations.

Titanium, while prone to higher displacement and stress transmission in certain configurations, remains the optimal choice for implants due to its lower deformation and better bone compatibility. High stress concentration at the abutment-implant interface warrants further exploration, as it may contribute to biological complications, including bacterial invasion and bone loss. Investigating screw-retained crowns and dynamic loading conditions would enhance the clinical applicability of the results. Kim *et al.* (2019) reviewed titanium's biocompatibility and lower bacterial adhesion compared to zirconia, suggesting that titanium remains the preferred implant material for long-term osseointegration [8]. Conversely, Duan *et al.* (2023) and Sales *et al.* (2023) conducted systematic reviews comparing zirconia and titanium implants, concluding that while zirconia implants demonstrate promising survival rates, their impact on bone remodelling and long-term stability remains less predictable [10,11]. Moreover, future studies should explicitly incorporate oblique loading conditions and investigate the biomechanical differences between screw-retained and cemented restorations using these materials. This investigation would allow for a more comprehensive assessment of their impact on stress distribution, load transfer, and potential failure points within the implant system, ultimately optimizing treatment outcomes.

5. Conclusion

This study developed a 3D model of a crown-implant-bone assembly to evaluate the biomechanical behaviour of combining zirconia and titanium in different implant system components and their influence on surrounding tissues. The finite element analysis findings suggest that zirconia abutments paired with titanium implants provide the most favourable outcomes for abutment screw interactions, when considering cemented crowns. This combination offers an optimal biomechanical balance, minimizing gingival strain, and favouring bone integrity preservation. Additionally, titanium remains the preferred material for optimal interaction with bone.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dental.2025.05.007.

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