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Research Article

Biomechanical Evaluation of a Single-Unit Implant-Supported Crown on ZrO_2 and TiO_2 Implants

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Abstract: The present study evaluated the biomechanical behavior, stress distribution, and bone microstrain in zirconia and titanium implants through tridimensional finite element analysis. A 3D partial maxilla was modeled containing 1.0 mm-thick cortical and cancellous bone tissue. A dental implant (3.3 x 10 mm) was placed in each model. The implants consisted of Titanium Monotype and Zirconia Monotype. A monolithic ceramic crown was installed on the implants. The models were imported into the analysis software and divided into meshes composed of nodes and tetrahedral elements. Each material was considered isotropic, elastic, and homogeneous. Therefore, all contacts were considered bonded, the cortical bone was fixed and an oblique load was applied (100 N; 30º). Microstrain and von-Mises stress (MPa) were selected as failure criteria. Comparable stress and strain values were shown in peri-implant bone for both implants. The maximum stress produced in the peri-implant region was mostly at the bone level. Under oblique loading, maximum von-Mises stresses and equivalent strains were more noticeable in the implant neck. Under an axial load, tension and strain were transferred to the peri-implant bone around the apex of the implant. The maximum tensile stresses that developed for either material were well below its fracture strength. Therefore, the highest stresses were mainly located in the distobuccal region of the neck for both implant materials in either loading condition. From a biomechanical perspective, yttrium-stabilized polycrystalline tetragonal zirconia implants can be a potential alternative to conventional titanium implants for implant-supported prostheses.

Keywords: Dental Abutments; Dental Implants; Dental Materials; Titanium; Zirconia.

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1. Introduction

Surrounded by the materials used in the manufacture of dental implants, titanium is still the dominant material for presenting excellent biomechanical properties and extensive scientific documentation with high long-term success rates. [1-4] Despite that, there is a constant discussion regarding the use of metal alloys in the human body. [5,6]

The grayish color of titanium is also a matter of discussion regarding its use in aesthetic areas, as it can create the darkening of the peri-implant mucosa in regions with a thin gingival phenotype [7] mainly affecting individuals with a high smile line.[8] To overcome these limitations of metallic implants, ceramic implants were developed, consisting predominantly of polycrystalline tetragonal zirconia ceramics stabilized with yttria (Y-TZP).[8]

The addition of 3% yttria allows the stabilization of its tetragonal phase at normal temperature conditions, thus enabling a subsequent transformation from tetragonal to monoclinic phase.[10] It leads to a microstructural increase in volume that prevents the propagation of cracks and, consequently, provides excellent toughness and strength properties. [10,11]

The literature still points out the excellent properties of Y-TZP concerning flexural strength, when compared to other restorative materials.[12-14] Several studies have also reported the excellent biocompatibility of zirconia implants concerning the behavior of peri-implant tissues.[15-17] Accordingly, one of the rehabilitative options is single-body or monotype zirconia implants, since clinical studies have shown promising results, as their surface seems to be less prone to biofilm formation.[18] Furthermore, the survival rate and maintenance of osseointegration of zirconia implants are similar to titanium implants.[19,20] Therefore, no evidence is currently available in the literature demonstrating the biomechanical behavior of zirconia and titanium implants. unique body. However, the present study aims to analyze the stress distributions and bone microstrain of an implant-supported prosthesis on single-body implants of zirconia and titanium through the validation of mechanical fatigue analysis and finite element analysis.

2. Materials and Methods

2.1. Survival Fatigue Analysis

The specimens were then subjected to a 0.5mm/min compressive load in a universal testing machine (Emic DL-1000, Emic, São José dos Pinhais, PR, Brazil) according to ISO 14801:2016 [22]. The specimens were positioned on a base with an angle of 30° about the base of the mechanical fatigue simulator (ER 37,000 Plus, Eros; São Paulo, Brazil) for the fatigue survival test and received 2,000,000 cycles at a frequency of 2 Hz and 200 N load with a 1.6 mm diameter stainless steel applicator, as described in ISO 14801:2016 [22], with the specimens immersed in distilled water at 37 °C. Fatigue resistance analysis was performed using the stepwise test described by (Matos et al., 2022) [23]. The samples were tested in a mechanical fatigue machine (Biocycle, Biopdi, São Carlos, Brazil), with the same device as the monotonic test, inclined at 30°, with a frequency of 10 Hz according to Matos et al. (2022) [23]. Load profiles were analyzed starting at 100 N with the load increasing at each following profile, at intervals of 10000 cycles. The number of cycles and the load at which the specimens fractured during the fatigue test was analyzed by the reliability software SPSS statistics (IBM, Chicago II, USA) using the survival analysis function, Kaplan Meier and Mentel-Cox (Log Rank) ($p<0.05$).

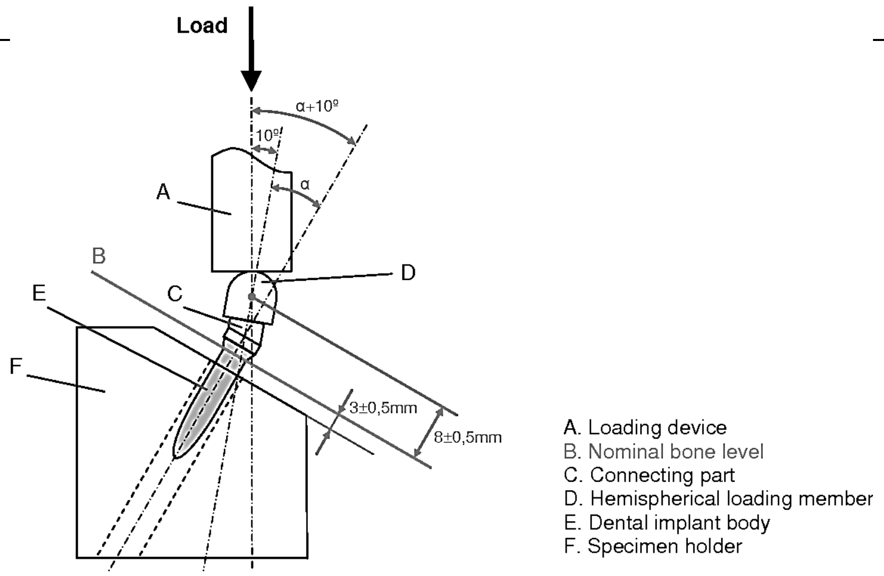

Figure 1. Specimen fixed on a base with 30º of angulation about the ground (ISO 14801:2016), Specimen being submitted to a compressive load of 0.5mm/min in a universal testing machine.

2.2. Finite Element Analysis

This study was conducted by numerical finite element analysis, which is a mathematical method used to investigate the biomechanical behavior of different dental implant systems. [21] Using CAD software (Rhinoceros 5.0, McNeel Europe™, Barcelona, Spain), all structures were modeled according to the specifications and geometry of each material and the set gave rise to the final model for each group. Thus, a three-dimensional (3D) structure was modeled to represent a section of the maxilla, containing cortical (1.0 mm thick) and cancellous bone tissue. [22] Based on the therapeutic possibilities for the same clinical indication, two different systems were formed. [22,24] The models were distributed in the respective study groups: Ti-S (control): titanium implant monotype (Ø 3.3 x 10 mm implant, Bone Level, Titanium Implant Monotype, Medens, São Paulo, Brazil) and Zr-S: Zirconia Implant Monotype. (Ø 3.3 x 10 mm implant, Bone Level, Straumann Dental System Implant, Basel, Switzerland).

After that, the maxilla section model was subjected to an implant according to the system of each group. A zirconia single-unit prosthesis (upper central incisor) was cemented over each implant. To simulate a condition closer to the clinical condition already reported in the literature, [22] a thin layer of resin cement 0.3 mm thick was added, [23] as shown in Figure 2.

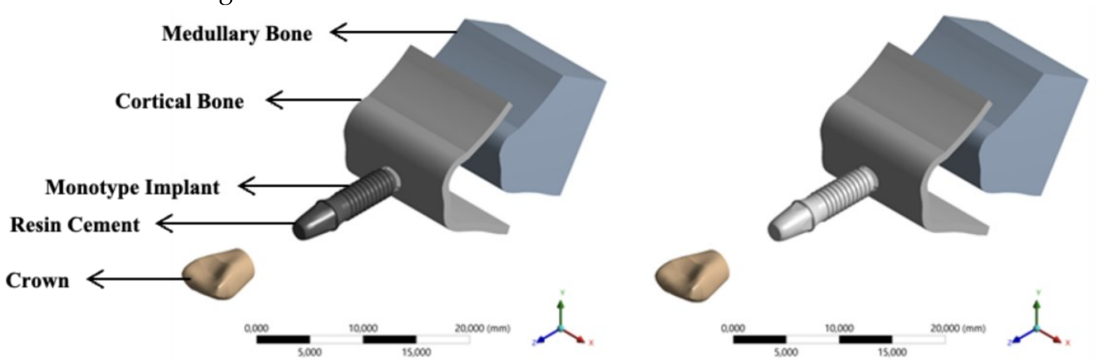

Figure 2. Illustrative of 3D models following the clinical sequence of an implant-supported prosthesis using titanium and zirconia single-body implant systems. Set consisting of a single implant-supported zirconia crown, cement film, monotype implant, cortical bone, and medullary bone.

Then, the solids were exported in STEP format (Standard for the Exchange of Product model data) for software analysis (ANSYS 17.2, ANSYS Inc., Houston, TX, USA). The external surface of the maxillary section was fixed in all directions, applying a static structural load of 100 N with an incidence angle of 30 º on the palatal surface of the central incisor. A mesh was created after the 10% convergence test [22,24] corresponding to 625,232 nodes and 338,842 tetrahedral elements for the evaluated models (Figure 3). All materials were considered isotropic, linear, elastic, and homogeneous. Between the implant and the bone, the contact was used to simulate complete osseointegration, [24], and the other contacts were considered bonded. Only one ceramic material was used for the structure of the implant-supported prosthesis: Yttrium Stabilized Tetragonal Polycrystalline Zirconia (YTZP). [63]

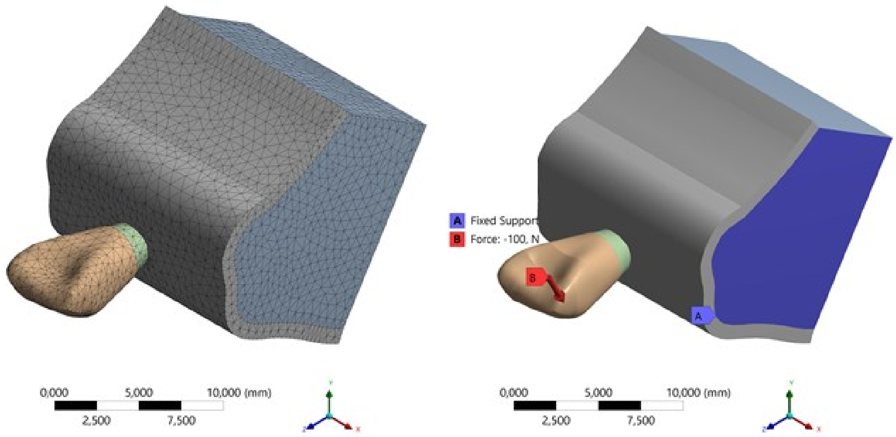

Figure 3. FEA details - Mesh, boundary conditions, loads, and connections.

The mechanical properties of the 3D model structures were defined based on the literature (Table 1). The results of the stress distribution according to the Von-Mises criteria were exhibited using visual plots with a scale in megapascals (MPa) for implants and ceramic structures. The microstrain criteria were used to investigate the bone behavior and its maximum values are shown in Table 2. [25,26]

Table 1. Distribution of the mechanical properties of the materials.

Material	Young's Modulus (GPa)	Poisson Ratio
Y-TZP [27]	220	0.30
Titanium [28]	110	0.32
Cortical Bone [29]	13.7	0.30
Cancellous Bone [29]	1.37	0.30
Oral Mucosa [30]	10	0.40
Resin Cement [31]	7.5	0.25

Stress and strain results that present values with a difference of less than 10% may be located in the convergence range of the analysis software, making it impossible to assume a significant difference. Consequently, the results that present a difference in peak values greater than 10% will be defined as significant. The results of each structure of both groups were compared qualitatively and quantitatively. Microstrain, von-Mises stress, and Maximum Principal Stress were adopted as failure criteria.

3. Results

3.1. Survival Fatigue Analysis

The stepwise test was also performed due to the absence of failure of any specimen at the end of the 2,000,000 cycles at a frequency of 2 Hz and a load of 200N. Thus, the means and confidence intervals for fracture resistance and cycles to fracture were obtained using the Kaplan-Meier and Mantel-Cox tests (log-rank, 95%), shown in Table 4. Study groups (short and long) were statistically similar in the number of cycles required for fracture (p=0.078), however, in fracture resistance, the long abutment group was statistically superior to the short abutment group (p=0.014).

Table 2. - 1-factor analysis of variance to verify if there is a difference between the maximum load resistance to fracture in both groups.

Group	Mean (Cycles)	SD	CI-Minimum	CI-Maximum
Ti-S	331573	13035	306023	357122
Zr-S	442405	11790	419295	465514

Group	Mean (Load)	SD	CI-Minimum	CI-Maximum
Ti-S	762	27.07	708	815
Zr-S	984	31.06	935	1032

The group's survival graphs are presented in figures 4.

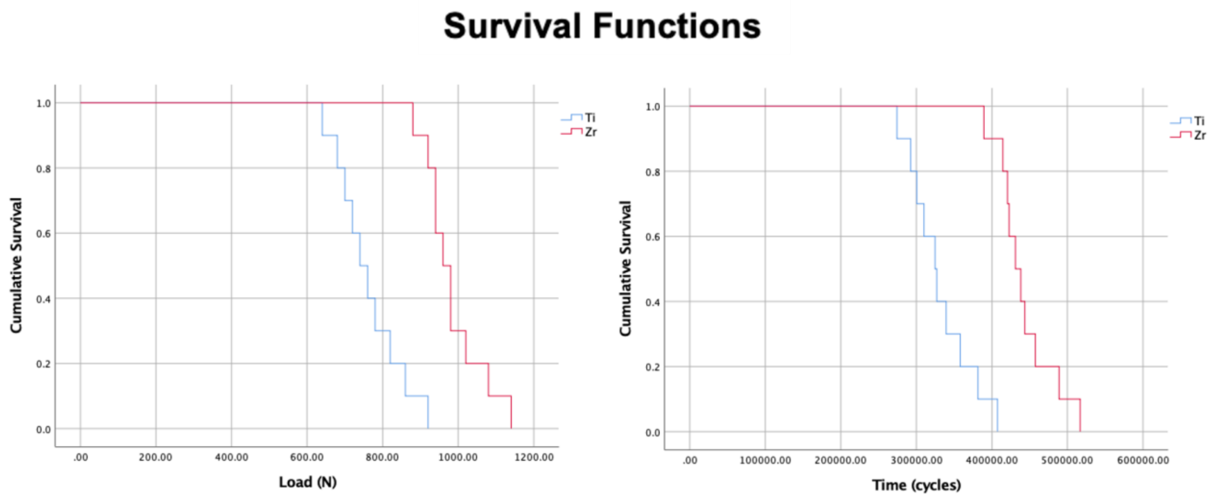

Figure 10. Survival graph of groups as a function of time (cycles) and survival graph of groups as a function of load (N).

Depending on the load or number of cycles, the probability of survival is different among groups. For example, with a 760N, the survival probability of the Ti-S is 87%. However, at 980N the long abutment has a 50% chance of survival, while the Zr-S group has no chance of survival.

3.2. Finite Element Analysis (FEA)

In an extensive qualitative analysis, the displacement of the implant prosthesis assembly can be verified in Figure 3A. Mechanical responses were calculated according to the failure criteria of each structure. For bone tissue, the results were analyzed in strain based on previous studies. [32-34] Observing the strain distribution represented in Figure 3B, it is possible to see that there is a similar response pattern between the models for the strain generated in bone tissue; however, the model with titanium implant shows a greater magnitude of a cervical strain than the model with zirconia.

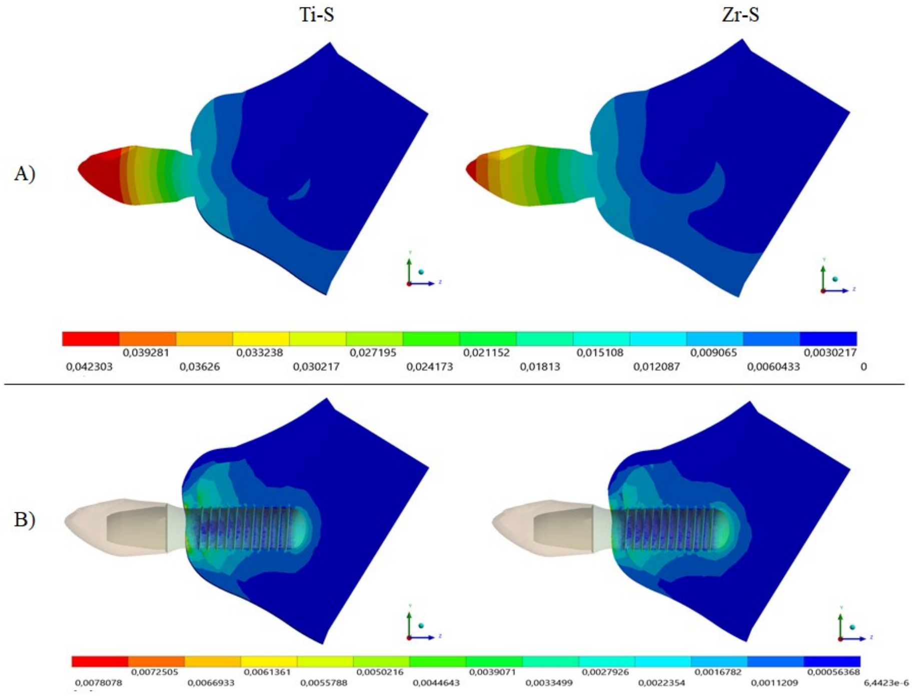

Figure 3. Illustrative of the 3D modeling qualitative analysis of Displacement and Strain Criteria on the structures of each group. A) Displacement Criteria. B) Strain Criteria. Left to Right: Ti-S: Titanium Implant Monotype; Zr-S: Zirconia Implant Monotype.

This behavior can be described by the tensile stress and von-Mises map in Figure 4. In ductile solids, such as titanium implants, the stress results followed the von-Mises criteria that help to show the fracture onset regions in the metals. However, for a comparative analysis between models, the generated results were obtained by von-Mises stress and also for the model with zirconia implant. The corresponding applies for the maximum principal stress, which highlights regions of tensile stress, the failure criterion for polycrystalline ceramics such as zirconia. Thus, both criteria show similar stress maps, but with different magnitude values, as plotted in Table 2. Thus, the zirconia implant concentrates more stress on its structure, reducing the energy required for its displacement (Figures 3 and 4).

Table 2. Quantitative analysis of von-Mises stress results in stress peaks (MPa) in the structures and bone microstrains (με) of each group.

Analysis Criterion	Group	
	Zirconia Monotype	Titanium Monotype
displacement (mm)	00.42	00.56
strain (μm/μm)	00.0780	00.0798
maximum principal stress (MPa)	280.76	250.11
von-Mises stress (MPa)	266.69	278.39

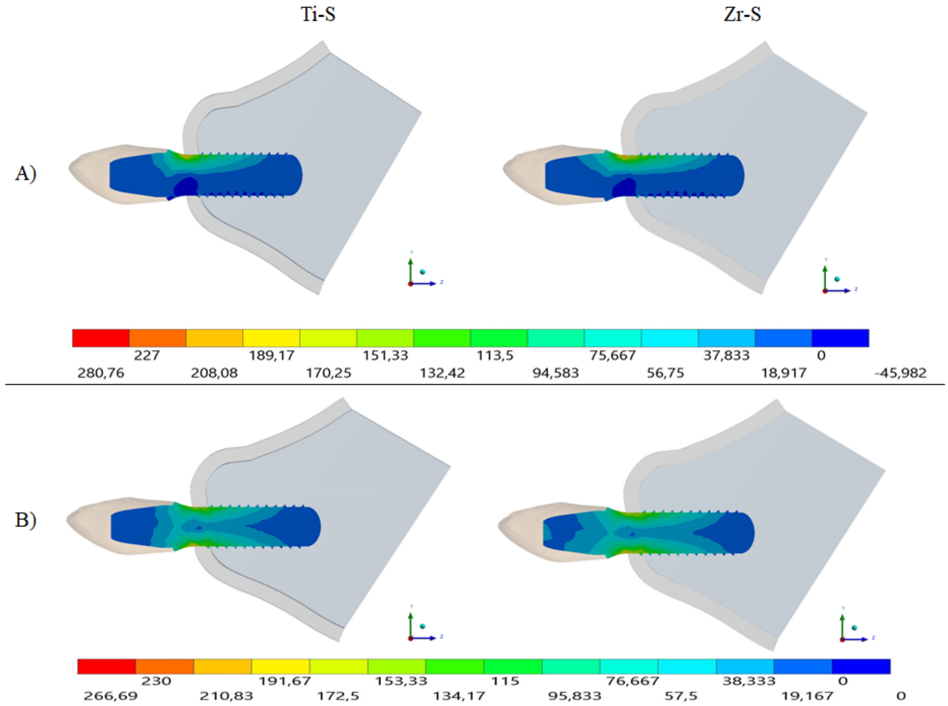

Figure 4. Illustrative of the 3D modeling of the qualitative analysis of Maximum Principal Stress and von Mises (Mpa) Criteria on the structures of each group. A) Maximum Principal Stress Criteria. B) Von Mises Stress Criteria. Left to Right: Ti-S: Titanium Implant Monotype (Control); Zr-S: Zirconia Implant Monotype.

4. Discussion

Finite Element Analysis (FEA) has been dentistry widely used, especially in implant dentistry, to assess stresses and strains in dental implants and adjacent structures.[30] The von Mises stress values were used to assess the stresses observed along the implants under loading. Von Mises stress values are defined as the combined effect of the three main stress components, resulting in a single value, which is indicative of the onset of stress distribution for ductile materials. [35] For implants, the maximum main stresses were also adopted as failure criteria, since failures occur when the tensile stresses are greater than or equal to the final strength of the material. [35,36]

The evaluation of the difference in biomechanical behavior between Zr-S and Ti-S implants in cases of an implant-supported prosthesis preceded possible clinical studies. Therefore, this study evaluated the behavior of implants with the different arrangements in the jaw region using computer models, as it allows the investigation of regions that are difficult to access by laboratory or clinical methods.[50] Admitting the fragile nature of ceramic implants, it was considered more appropriate to use non-braided implants with autonomous fixation systems. For that reason, bone board designs allowed the rotation of the implant-supported prosthesis during palatal loading and the torsional load transmission to the implants in an axial direction. [37,38] In turn, enabling the prevention of overloads on the implant, since this function results in a greater force transmission transferred to the marginal bone crest. [37-39]

The materials used to manufacture endosseous dental implants can be classified according to their chemical composition in metals, ceramics, or polymers. [11,64] Metals, with an emphasis on Ti and its alloys, have been a preferred material and are expected to last in long term.[39] Countless investigations have demonstrated the reliability of this material for medium- and long-term use. However, a growing number of studies report a need to find an alternative material to titanium, especially Y-TZP. [40-42] Zirconia, as a ceramic oxide, has superior resistance to corrosion and wear. Considering that they are in the highest oxidation state, it has high stability in the oral cavity. [11,43,64]

Several studies using FEA have compared the biomechanical loading responses between Zr and Ti implants. [44-47] However, most of them had single-body implants in the anterior region of the maxilla, with modeling of the cortical and solid cancellous bone in anatomical and geometric configurations of little complexity. These studies revealed comparable [44] or even lower [45] stress distributions in the peri-implant bone for the Zr implants. Another study evaluated the behavior of three different Zr implants and their influence on peri-implant bone and concluded that compared with titanium implants, different geometries can affect stress patterns at the bone level. [46]

The results of the mentioned studies cannot be directly extrapolated for comparison with the current analysis due to the difference in loading, geometry, and simulated superstructure. However, a general trend can be observed. According to previous studies, similar stress distribution patterns for both implant materials suggest that, biomechanically, Zr-S implants may be a potential alternative to Ti-S implants to support the single-unit prosthesis.

Okumura et al. [48] evaluated the biomechanical behavior of implants with different compositions and their relationship with maxillary cortical bone thickness, geometry, and material diameter. It can be seen that, for both implants, under axial load, the stress peaks were located in the bone around the apex of the implant, and under oblique loading, the stresses were transferred to the bone around the first threads of the implant. In the absence of cortical bone, there was no difference in the behavior of the evaluated implants. Other authors have observed that implants with an apex near the sinuses or nasal cavity have limited bone availability to resist axial loading, which transfers apex tensions to the entire implant body. [47,48] Despite the differences in bending behavior given by the different elasticity modulus of both implant materials, minimal differences were observed in the microstrains values in the peri-implant bone. This finding can be attributed to the fact that the implant materials are much more rigid than the surrounding cancellous bone. Thus, implants tend to show greater displacement and less strain under axial load, consequently, less influence of the different elasticity modulus of the implant materials on bone strain values.[47] This may suggest that, in the presence of rigid cortical bone in the alveolar crest, different tension levels may be observed between both materials.

The stresses recorded on the Ti-S and Zr-S implants were not clinically critical, as the mechanical properties of the implant material itself can withstand much higher stress magnitudes than those recorded in this analysis. Grade 4 Ti Implant is known to tolerate stresses of up to 500 MPa without irreversible failure.[51] Therefore, stress values of 250.11 MPa and 278.39 MPa generated in implants under vertical forces, respectively, are unlikely to cause implant failure. In Zr-S implants, the maximum tensile stress values under vertical load were 280.76 MPa and 266.69 MPa, thus being well below the flexural strength of the material (700 to 800 MPa). Hence, Zr-S implants exhibited a more apical stress distribution compared to Ti-S under oblique loading. This may be attributed to the higher elasticity modulus of the Zr-S implants used in this study. Clinically, the indiscriminate distribution of tensile stresses across the implant body may result in a more favorable physiological and biomechanical bone environment, with less force transmitted to the bone-implant interface. Comparable stress values for both implant materials were expected, considering that the two materials involved have Young's modulus within a close range (Ti-S, approximately 110 GPa; Y-TPZ, approximately 220 GPa). [27,28] Since minimal differences in stress variations can be observed in Young's modulus between the materials tested. However, a variation greater than five to seven times normal is necessary for these changes to be considered significant. [52]

According to Wolff's law, mechanical load in the bone environment can act as a possible stimulus that governs the adaptive bone response.[53] Frost defined minimum (50 to

100 με) and maximum (3,000 με) values below and above which bone loss will occur due to atrophy due to disuse or pathological overload.[53-55] The absolute values of bone strains were 0.0780 and 0.0798 με for the zirconia and titanium implants, respectively, equivalent values with physiological bone remodeling according to Frost's law. However, there was an approximately 10% increase in strain value when Ti-S was used as an implant material. This can be explained by the difference in the modulus of elasticity between the two materials. In the presence of 1 mm of cortical bone, less rigid Ti-S implants tend to deform more compared to more rigid Zr-S implants, thus transmitting greater stresses to the peri-implant bone near the first threads of the implant.

Due to the fracture toughness, high zirconia strength, excellent biocompatibility, low radioactivity, and significant aesthetic properties, Y-TZP can be a possible alternative to be used instead of Titanium.[56] In the present study, the comparable stress and strain values observed for both implant materials suggest that Zr-S implants can be used as an alternative to Ti-S-based implants for support and retention of implant-supported prostheses.

The physical properties of all structures modeled in this study were simplified since all materials were considered homogeneous and have a linear response to stress and strain. Therefore, the complicated anisotropic behavior of bone was modeled as a homogeneous isotropic material. Perfect osseointegration between implants and bone was assumed and stress analysis was performed using a static structural load. However, like any other basic research device, FEA helps in planning further in vitro tests and clinical trials when used as an initial step.

5. Conclusions

Based on the outcomes of this in vitro study, the following conclusions can be drawn:

a) From a biomechanical behavior, single-body ceramic implants, composed of tetragonal polycrystalline zirconia stabilized with yttrium, can be a viable alternative to titanium implants for single prostheses.
b) Zirconia Pure Ceramic Implant Monotype presented the best monotypic static structural load response, as it concentrated a greater number of microstrains of the implant collar, not being possible to reduce the strength of the restorative system, consecutively greater flexural strength in long-term.
c) The validation of this study requires in vivo investigations through the placement of zirconia and titanium monotype implants in the anterior region of the maxilla with a follow-up of 2 years to overlap the clinical information with radiographs to corroborate the in vitro and silico tests documented in the literature.

Author Contributions: Conceptualization: J.D.M.d.M., N.C.R., D.A.Q., and G.d.R.S.L.; methodology, J.D.M.d.M., N.C.R., D.A.Q., A.L.S.B., and G.d.R.S.L; formal analysis, J.D.M.d.M., N.C.R., D.A.Q., A.L.S.B., and G.d.R.S.L; investigation, J.D.M.d.M., N.C.R., M.A.C.S., D.A.Q., A.B.B., A.L.S.B., and G.d.R.S.; data curation, J.D.M.d.M., N.C.R., M.A.C.S., D.A.Q., J.U.R.S., C.A.d.O.A., A.L.S.B., and G.d.R.S.; writing— J.D.M.d.M., N.C.R., M.A.C.S., D.A.Q., J.U.R.S., C.A.d.O.A., A.L.S.B., and G.d.R.S.; writing—review and editing, J.D.M.d.M., N.C.R., M.A.C.S., M.A.B., and G.d.R.S.L.; supervision, M.A.C.S., M.A.B., and G.d.R.S.; project administration, M.A.B., and G.d.R.S.L; funding acquisition, J.D.M.d.M. All authors have read and agreed to the published version of the manuscript.

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