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Comparative Stress Analysis of Polyetherketoneketone (PEKK) Telescopic Crowns Supported by Different Primary Crown Materials

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Abstract: The present study aimed to investigate the stress distribution of secondary telescopic crowns made of polyetherketoneketone (PEKK) combined with different primary crown (PC) materials (Zirconia, CoCr, Titanium, and PEKK) using finite element analysis. The geometric model was composed of bone tissue, periodontal ligament, root dentin, cement layer, primary crown, and secondary telescopic crown (SC). A total of four models were evaluated in which the secondary crowns were simulated in PEKK. The models were designed in CAD software and exported to the computer aided engineering software for the statistic structural analysis simulation. The materials were considered isotropic, with linear behavior and elastic properties. The model was fixed in the bone base and the load was applied at the occlusal surface of the crowns with 600 N. The results were required in von-Mises stress for the primary crown, secondary crown, cement layer, and Equivalent Strain to the periodontal ligament and bone tissue. Results show that the material influenced the stress distribution. The higher the PC elastic modulus, the higher the stress magnitude on the SC and cement layer. In the present study, the use of milled high-density polymer for primary crown presented a promising biomechanical behavior as an alternative material for double-crown design.

Keywords: finite element analysis; dental materials; restoration; polyetherketoneketone; polymer

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1. Introduction

The telescopic prosthesis is an overdenture treatment modality in which the denture is partially supported by abutment teeth or dental implants [1]. This treatment modality requires the use of a double crown as an attachment system. Therefore, the primary crown is cemented to the abutment, while the secondary crown is attached to the base of the prosthesis [2,3]. According to the literature, this complex retention system is worth it since efficient force dissipation can be achieved [4], associated with more effective oral hygiene; and maintenance of periodontal tissue health [1–3]. In addition, the rehabilitation presents satisfactory esthetics and a good survival rate [5–7].

There are different conditions thoroughly described in the literature that can affect the oral cavity, such as dental caries, abnormal teeth, enamel hypoplasia, supernumerary teeth, and dental agenesis [8]. A syndromic patient with a complex case has to be treated using a multidisciplinary approach and in particular, needs a prosthetic rehabilitation for

the restoration of missing dental elements in the arch such as telescopic overdenture on natural teeth [8].

The telescopic prosthesis overdenture is a prosthetic rehabilitation with the particular advantage of being indicated in severe cases of horizontal and vertical soft tissues loss [9]. This restorative approach allows obtaining good esthetics by recovering the naso-labial angle obtained with the prosthesis flange, a feature that is not present with fixed prosthesis even with osseo-densification techniques [8–10].

Regarding chewing load dissipation, it is important to note that there are differences between implant-assisted overdenture rehabilitation and telescopic-crowns overdenture on natural teeth [11]. Since the periodontal ligament is conserved as well as the anatomic roots, the overdenture on natural teeth will dissipate the masticatory forces lighter and consequently with less stress on the prosthetic components. Therefore, it can justify the orofacial system with a lower incidence of orofacial pain and temporomandibular disorders for this prosthetic modality [8–17].

Despite the reported benefits, the double crown retention system can be affected by the manufacturing method and design parameters. In cylindrical crowns, the retention is performed mostly due to the friction between the primary crown's external surface and the secondary crown's intaglio surfaces [2,18]. Cylindrical crowns have technique sensitivity, difficulty in manufacturing, increased misfit, and progressive wear; therefore, conical crown design is preferred as it may reduce these undesired effects. The conical design system promotes a wedging action strong enough to assist the prosthesis retention. In addition, the conicity between primary and secondary crowns allows a manufacturing process less sensitive to the technique and wear between the contacting surfaces [2,18,19].

Conventionally, casting and electroforming techniques are applied to manufacture telescopic crowns. When using the conventional casting method, the lost-wax technique should be applied using precious alloys. Nonetheless, since their high cost, time consumption, and difficulty in using the paralleling device, telescopic prostheses are not considered as the primary treatment option for dental prostheses [1,2]. However, with the aid of digital dentistry, telescopic dentures can be reliably manufactured with stable retentive forces using customized design features while reducing the processing time and technical errors [1–3]. Furthermore, the modeling software allows for design adjustments prior to crown manufacturing [2,20] and with a wide range of materials.

The most common dental materials used in the double crown-retained systems for removable dentures are titanium, non-precious metal alloys, precious metal alloys, zirconia, and high-density polymers [polyaryletherketone (PAEK) family]. The use of high-performance thermoplastic polymers is indicated since they present high strength, rigidity, excellent biocompatibility, and fast processing [21]. In the dental field, Polyetherketoneketone (PEKK), a member of the PAEK family, has already been used in removable dentures [22], temporary prostheses, intrarradicular posts [21], crowns [23] implant-supported frameworks [24], and fixed dental bridges [25,26]. In addition, a previous in vitro study [16] evaluated the retention forces of secondary crowns made of PEKK when combined with primary crowns made of different materials. The study showed acceptable forces for overdenture retention regardless of the primary crown material. However, there are no studies available that investigated the stress distribution between PEKK secondary crowns in combination with primary crowns made in different materials.

Therefore, the present study aimed to investigate the stress distribution of secondary telescopic crowns made of polyetherketoneketone combined with different primary crowns materials. The null hypothesis was that the PEKK secondary crowns would present a similar mechanical response when supported by different primary crowns during chewing load incidence.

2. Materials and Methods

The geometry of the abutment tooth was chosen to resemble a mandibular first molar (Figure 1). The entire model was designed based on parameters reported in a previous

study [4], which considered an axially symmetrical abutment to be sufficient for investigating the main effects on the subject structure (Figure 2).

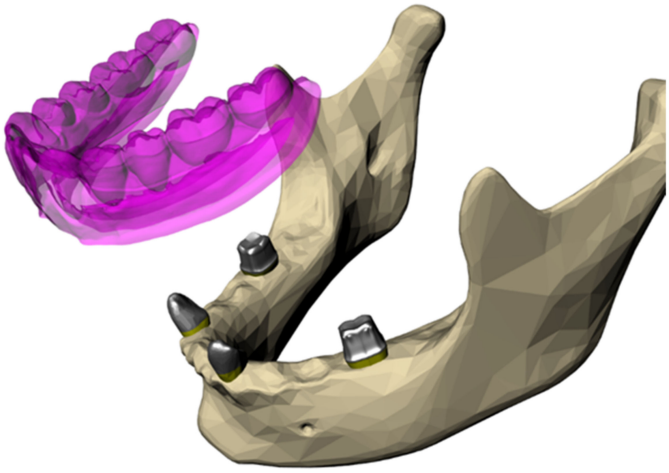

Figure 1. Schematic illustration showing the full-denture and the telescopic primary crowns in molar and canine abutment teeth.

In addition, the root dentin, periodontal ligament, and bone tissue were designed according to the study by Borges et al., 2021 [27].

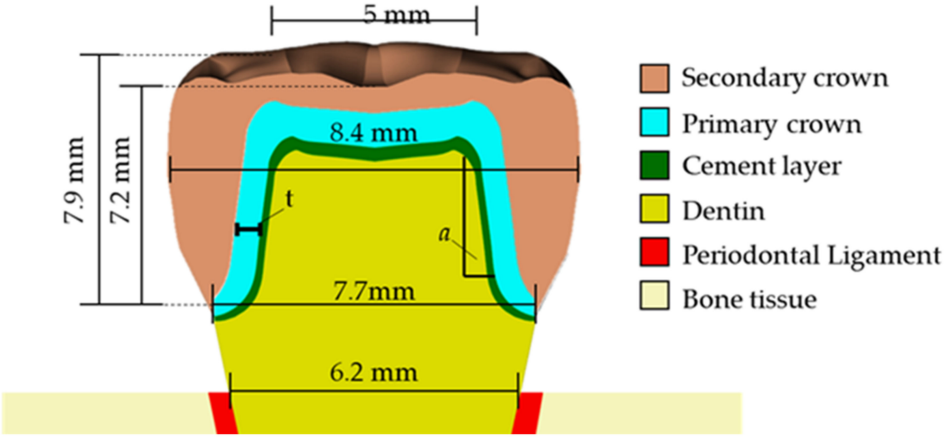

Figure 2. Cross-section of the geometrical model with the designed dimensions.

The crown preparation presented 5.75 mm height [4] and axial walls (*a*) with 6° of divergence [4]. A uniformly thick (0.3 mm) layer of resinous cement between the prepared tooth and the PC was also included in the model. The primary crown (PC) presented 0.80 mm minimal thickness (*t*), while the secondary crown (SC) was designed with minimal thickness of 1.5 mm. In the present model, the tooth was supported on a bone cylinder. Then, the solids were exported in Standard for the Exchange of Product Data (STEP) format to the computer aided engineering (CAE) software (ANSYS 19.2, ANSYS Inc. Houston, TX, USA). In sequence, the mesh subdivision was generated through the convergence test until obtaining a finite number of nodes and elements for the models (Figure 3). The mesh density was defined after the contacts verification of coincident nodes between the juxtaposed solids as well as the mesh convergence test considering the linear trend of von-Mises stress peak by the number of elements. It is important to note that only one model was used in the present simulation, and the difference between the molar size and shape, as well as the size of the preparation, were assumed as a constant in the results. Therefore, the present model geometry was considered in the results analysis; however, differences in the axial walls angle, adhesive area, parafunction (bruxism), dilacerated roots, endodontic treatment, presence of biomaterials build-up, and

several other possible variables can be found in the molar structure, which were assumed as ideal since this was a homogeneous prepared tooth.

For all materials simulated in the model, linear-elastic, isotropic material was considered based on 2 constants: Elastic modulus and Poisson ratio. Table 1 summarizes the simulated material properties.

Table 1. Mechanical properties of the materials/solid geometries used in the current study.

Material	Elastic Modulus (MPa)	Poisson Ratio
Dentin	18,600	0.23
Bone tissue	13,700	0.30
Resin cement	8000	0.30
Zirconia (3Y-TZP)	200,000	0.30
Titanium (Ti-6Al-4V)	110,000	0.30
CoCr	220,000	0.30
PEKK	5100	0.40

To accurately simulate the movement and loosening process of the system, knowledge about the coefficients of dynamic and static friction (μ and μ0, respectively) between PC and SC was required [4]. However, in this study, μ = μ0 was chosen due to the absence of information in the literature regarding the true values between the simulated materials [4]. Therefore, frictionless contact was assumed between the juxtaposed structures. The other layers and structures were considered perfectly bonded.

A static structural evaluation was performed using a single-step analysis. Boundary conditions defined the fixation support at the bone base, and the load (600 N) was applied at the occlusal surface of the crown (*Z*-axis) (Figure 3). The load value was based on previous finite element studies that have evaluated the mechanical behavior of posterior tooth, assuming it as a normal value of chewing force [28,29]. The base surface of the bone was restricted in the X, Y, and Z directions [4]. The results were required in von-Mises stress in both crowns and cement layer; and the Equivalent Strain in the bone and periodontal ligament (PDL). The stress and strain peaks were recorded from each structure based on the maximum probe tool for a quantitative comparison between the conditions.

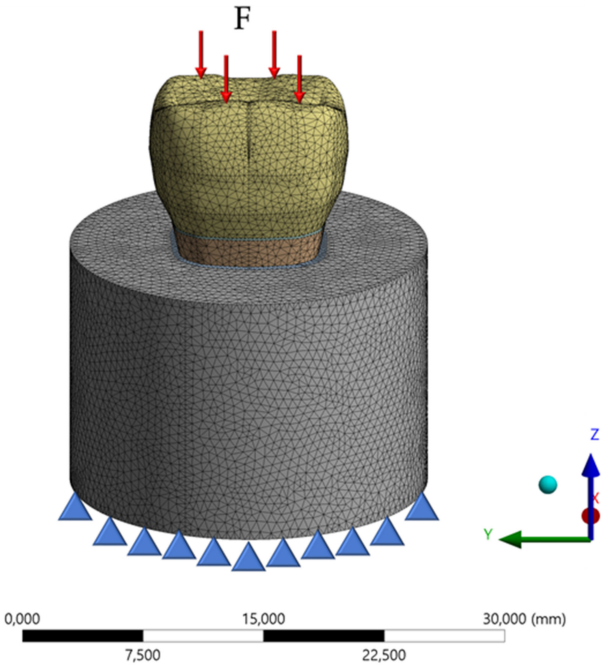

Figure 3. Finite element model after meshing process and boundary conditions applied in the simulation.

3. Results

After the numerical calculation, von-Mises stress (MPa) and Equivalent Strain results were obtained for each simulated condition. The stress data were summarized using colorimetric maps (Figures 4–8). The stress peaks in each structure were reordered and summarized in Table 2. The Yield strength of crown materials is summarized in Table 3. The red color indicates the maximum value obtained by calculation as a standardized limit to show difference between the models. The strain is the elongation or deformation of the material that undergoes stresses. The required energy to store the total strain on the whole body is the strain energy, summarized in Table 2 according to the different materials combination.

Table 2. Outcomes based on stress peak values (MPa), micro-strain, and strain energy (mJ), according to the primary crown material.

Model (PC + SC)	Stress (MPa)			Microstrain		Strain Energy (mJ)
	SC	PC	Cement Layer	PDL	Bone	
PEKK + PEKK	158.3	46.4	2.15	126	365	0.111
Titanium + PEKK	152.2	67.5	3.28	126	364	0.115
Zirconia + PEKK	151.1	68.8	3.29	125	365	0.115
CoCr + PEKK	150.9	68.9	3.29	125	366	0.115

PC, primary crown; SC, secondary crown; PDL, periodontal ligament.

Table 3. Yield strength of crown materials.

Material	Yield Strength	References
PEKK	165 MPa	[30]
Titanium	519 MPa	[31]
Zirconia	1190 MPa	[32]
CoCr	540 MPa	[33]

For the Von-Mises stress (Figure 4), a similar stress trend was calculated regardless of the PC material. However, the lower the rigidity of restorative material, the higher the stress concentration on the SC intaglio surface near the load application area. In addition, for the restoration margin, similar stress magnitudes were observed irrespective of the crown materials. The restoration failure risk consisted of the material highest peak divided per its strength [34] and is summarized in Table 4. It is possible to observe that regardless of the material combination, that SC presents superior failure risk in comparison with the PC. In addition, all PC showed reduced failure risk. With only a 0.05 difference between the calculated ratios for the SC, the clinical behavior and the use of fatigue methods were necessary to indicate a significant difference between the models.

Table 4. Failure risks for primary and secondary crown according to the different materials combination.

Model (PC + SC)	Failure Risk	
	SC	PC
PEKK + PEKK	0.96	0.28
Titanium + PEKK	0.92	0.13
Zirconia + PEKK	0.92	0.06
CoCr + PEKK	0.91	0.13

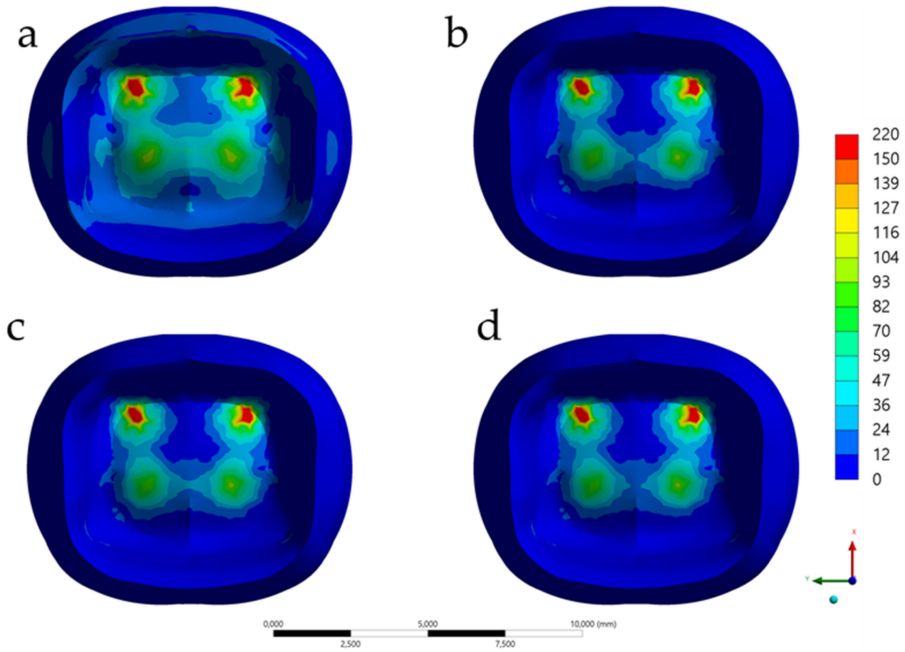

Figure 4. Stress distribution (MPa) in the secondary crown's intaglio surface according to the PC restorative material: (**a**) PEKK; (**b**) Titanium; (**c**) CoC; and (**d**) Zirconia.

Primary crown (Figure 5) stress analysis showed a proportional pattern of distribution between the structures as the restorative material elastic modulus decreased. However, for this structure, the effect of restorative material was more evident, with lower stress concentration in the PEKK–PEKK combined model. The occlusal surface showed high stress magnitude; however, this was the case in all models regardless of the restorative material.

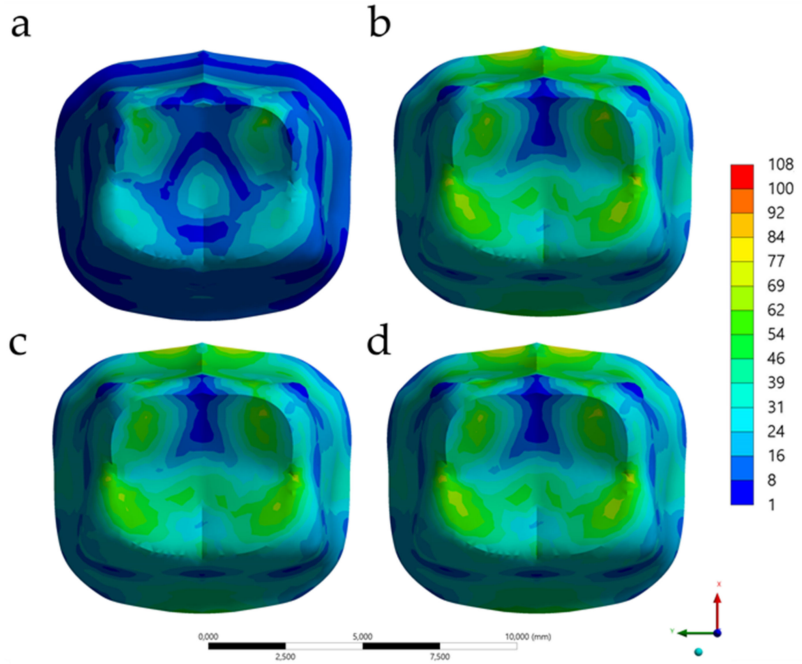

Figure 5. Stress distribution (MPa) in the primary crown's occlusal surface according to the restorative material: (**a**) PEKK; (**b**) Titanium; (**c**) CoCr; and (**d**) Zirconia.

For the PC, the stress peaks ranged from 46.4 to 68.9 MPa. These differences in stress values were proportional to the material stiffness. Therefore, the higher the elastic modulus of the primary crown, the higher the stress magnitude in its structure. A similar

effect was observed for stress in the resin cement layer (Figure 6), showing that flexible primary crowns protected the adhesive interface from stresses during compressive loading. Therefore, the stress magnitude in the adhesive interface could be affected by different combinations of crowns in the telescopic attachments.

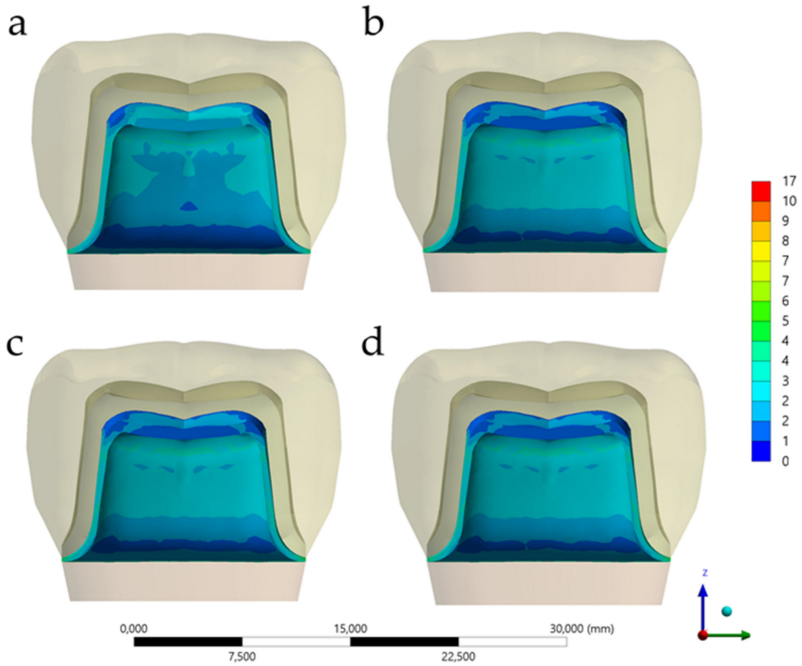

Figure 6. Stress distribution (MPa) in the cement layer according to PC material: (**a**) PEKK; (**b**) Titanium; (**c**) CoCr; and (**d**) Zirconia.

For the periodontal ligament and bone (Figures 7 and 8) model analysis, results showed that the PC material did not influence strain outcomes.

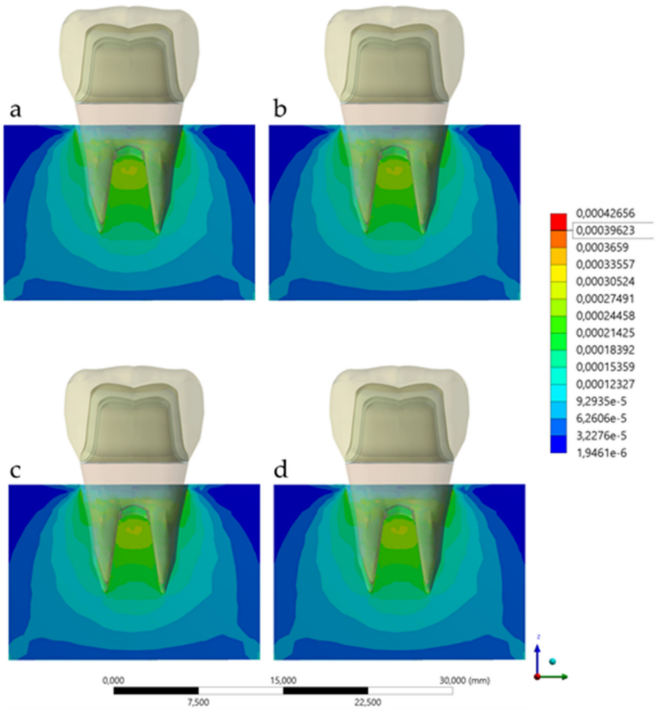

Figure 7. Strain distribution in the bone tissue according to the PC material: (**a**) PEKK; (**b**) Titanium; (**c**) CoCr; and (**d**) Zirconia.

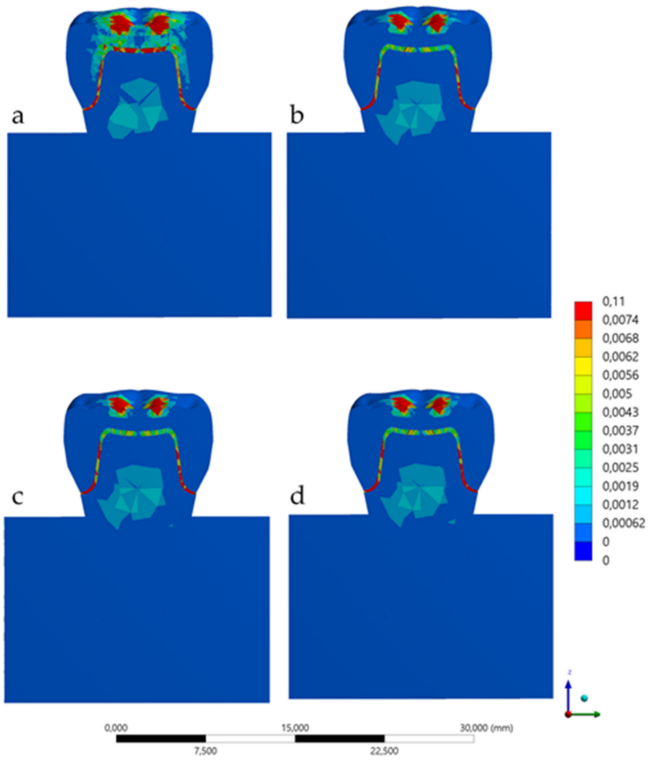

Figure 8. Strain energy (mJ) in the set according to the PC material: (**a**) PEKK; (**b**) Titanium; (**c**) CoCr; and (**d**) Zirconia.

4. Discussion

The null hypothesis was that PEKK primary crown could present a similar mechanical response when supported by different primary crown materials during chewing load incidence. The results showed that the primary crown material influenced the biomechanical response of the telescopic attachment system. Thus, the hypothesis of the present study was rejected. It was observed that the restorative material with high elastic modulus allowed less stress to reach the cement layer; however, it increased the stress magnitude in the primary crown as well as in the secondary crown's intaglio surface. In addition, a previous study affirmed that a more flexible dental material was a promising alternative for telescopic crowns systems [20]. This study complements this finding, showing that the PC material stiffness can modify the stress concentration in the set during compressive loading.

The use of a milled telescopic crown is indicated to improve the long-term longevity; therefore, the proper digital workflow must be considered to ensure clinical success with predictable retentive force and abutment maintenance [2,3,20]. Therefore, reports suggest high risk for debonding when considering the stress magnitude at the cement layer [25–28,35–37]. In the present simulation, the models with zirconia in the PC showed the highest stress at the cement layer in comparison with PEKK.

Previous studies reported that stress during secondary crown removal could be affected by the shape of the preparation model and the shear force between primary and secondary crowns [4]. In relation to this, the findings of the present study suggest that primary crowns should be selected to avoid higher stress concentration in the presence of compressive occlusal forces. Considering the retention, path of insertion, and ease of insertion of over-dentures, the recommended angle of convergence for the telescopic system is between 0° and 6° [4]. The present study used 6°, as the maximum angle possible to represent the conical system.

According to a review evaluating the clinical behavior of telescopic crowns, the success rate for conventional telescopic crown retained removable partial dentures was approximately 95.1%. In addition, the three most common complications for overdentures were the need for relining (34.8%), facing repair (26.95%), or re-cementation of primary crowns

(20.6%) [38]. Based on that, the present results suggest that PEKK material can offer a more reliable treatment option in terms of stress reduction on the cement layer and, therefore, potentially minimizing the incidence of primary crown re-cementation.

The stress level in the cement layer is usually proportional to the debonding failure risk [25,39], and thicker cement layers will promote higher stress magnitude due to the higher polymerization shrinkage [38,40]. However, in the present study, all models were simulated with a uniform cement layer thickness [25] to allow standardized comparison between groups; however, clinically, cement layer thickness differs. In addition to the evaluated materials, the masticatory load can also affect the mechanical response to the removable denture treatment [26,39]. In the present study, axial loads were applied in order to simulate the most common load (axial) in the posterior region of the mouth [25]. However, as the dentures have free end saddles, the load on the cantilever arm should also be considered [26,27,35–37]. Therefore, it is possible to suggest that the non-axial chewing loads can negatively influence the telescopic crown system mechanical response in comparison with the axial loading. However, the effect of different load orientations can be evaluated in further studies.

In terms of resistance to occlusal loads, PEKK based full crowns show a fatigue limit above 720 N, a value considered sufficiently high to resist fracture in clinical conditions [13]. Therefore, it is reported that PEKK crowns offer a stable treatment option for patients, in particular for those that suffer from metal allergy [13]. These findings complement the outcomes of the present study, as high resistance to occlusal loads and low-stress magnitude on compressive loading support the use of PEKK as a suitable telescopic attachment system for over-dentures.

A previous study investigated the retention forces between primary and secondary telescopic crowns milled from various materials [1]. According to the authors, the material combination in telescopic attachments affected the retention forces and wear, with the combination of Titanium and PEKK presenting a promising result [1]. The present study supports their finding, suggesting that the combination between titanium and PEKK is a suitable option since this model showed an intermediate behavior. However, if a metal-free treatment is planned, the use of Zirconia or PEKK primary crown is a suitable option. Interestingly, the study by Kamel et al. evaluated the performance of telescopic crown material combination, including PEKK-PEKK, Zr-PEKK, and CoCr-PEKK [2]. They observed that the maximum retention force was exhibited by PEKK–PEKK crown combination, in comparison to the other groups. In addition, the authors reported that the long-term friction force remained constant during the evaluation [2]. These findings are in line with the present study, which showed the combination of PEKK–PEKK crowns to be most promising for telescopic crown retained overdentures.

Previously, in vitro investigations compared retention forces of secondary telescopic crowns made of PEKK in combination with primary crowns made of four different dental materials [25]. According to the authors, all tested primary crown materials (PEKK, Zirconia, Gold, and Non-precious metal alloy) with a high-performance polymer PEKK as the secondary crown reached acceptable forces for overdenture retention over a period equivalent to 10 years of use [26]. Therefore, the materials combination affects the retention of telescopic crowns, as reported before [6]. In a study by Wagner et al. [6], telescopic crowns made from PEEK showed stable retention load values [6]. The present study showed similar findings, showing low-stress concentration on PEKK material, which is a result of its low elastic modulus and high strength properties.

Previous studies have compared the stress induced in the mandible around implants, using two different attachment systems, locator, and telescopic crowns [35]. According to the authors, the locator attachment may demonstrate superior clinical performance compared to telescopic in terms of stress concentration [34,35]. However, for tooth-supported retention systems, the locator system is less suitable. In addition, comparing the stress distribution in mandibular implant-supported overdentures and tooth-supported overdentures with telescopic crowns, it is reported that the implant group presented more stress

concentration in the bone compared to the teeth-supported model [36]. This is attributed to the presence of periodontal ligament and more rotational freedom to dissipate the loads in the lever arm [36]. However, these studies did not assess stress concentrations and complications around PEKK abutments. In a study by Emera et al. [37], strain gauge analysis was performed around implants with telescopic attachments of different materials combinations (Zr-Zr, PEKK-PEKK, and Zr-PEKK). Zr-PEKK combination telescopic attachments showed the least strain transmitted to the implants. It is pertinent to mention that implant overdentures were not assessed in the present study. However, the findings of the present study are in line with the study by Emera et al., as there was no difference observed in bone-tissue and periodontal ligament mechanical response for all evaluated models in the present study (including Zr-PEKK).

During the designing of an in silico study, inherent methodological limitations were inevitable. The intra-oral condition with different chewing loads incidences and patient's habits were not considered. In addition, the materials were considered isotropic without a defect population. The FEA model consisted of no misfit between PC and SC and the cement layer was homogeneously distributed [25,27,39]. In addition, the distribution of applied forces on the occlusal surface of the tooth model was not considered as a factor. Previous reports have already demonstrated that the tooth anatomy, cusp height and angulation, antagonist, number of contact points, and root shape can modify the stress distribution during compressive loading [40–42]. Therefore, it is important to mention that an irregular occlusal shape with perpendicular forces applied to the X and Y-axes can present oblique components inherent to the model geometry. As all the models presented the same shape and design, this effect can be reduced between the results comparison, but not directly extrapolated for different clinical scenarios. Although the finite element method generates useful information about the mechanical response of determined conditions, clinical extrapolations may not be accurate due to the presence of simplifications and lack of biological aspects. However, on the basis of the present study findings, further randomized controlled trials are warranted to validate the efficacy of PEKK overdenture telescopic crown abutments. Further prospects for the development of this technology can be benefited by the optimal loading distribution of PEEK in this clinical scenario, evaluating different convergence angle for the primary crown axial walls, luting procedure, and long-term fatigue.

Considering similar materials (PEKK/PEKK) for PC and SC, their surfaces may deform, but the size of the contact area may not change considering the similar elastic modulus. In this scenario, the horizontal displacements are limited by the crown shape and only deformations are possible. Therefore, for PC and SC made of different materials, further studies should evaluate the friction to proper evaluate the displacements and deformation during chewing loading. In addition, further simulations considering the S-N curve of each material should be performed to evaluate the proper long-term fatigue effect of this attachment system with the incidence of compressive chewing loads.

The simulation considering the linear-elastic behavior is the simplest approach to interpret results based on the relationship between stress and strain in the simulated materials. Before a determined strain level, the materials tend to present the strain-stress behavior in a linear way. However, when the strain limit is reached, the material will either break, yield (not elastic anymore), or it will behave as a non-linear elastic solid [42]. The literature reports that linear dental material models simulated in FEA can provide an understanding of the range in magnitudes of the specific material properties of the tooth components, however, the results should be carefully evaluated before being adopted by researchers in dentistry [43].

5. Conclusions

The material combination in telescopic attachments influences the stress magnitude during compressive loading. The use of milled high-density polymer (PEKK) for primary crown presented a promising biomechanical behavior as an alternative material for a

double-crown attachment system. The use of PEEK in the secondary crown requires further evaluation due to the high failure risk.

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