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Research Article

Finite-Element Analysis of the Effect of Utilizing Various Material Assemblies in "All on Four" on the Stresses on Mandible Bone and Prosthetic Parts

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Background. Fixed prostheses often utilize the "All-on-four" technique, in which four implants are inserted into the jaw bone, and a framework supports them. Titanium is usually used in the fabrication of "All-on-four" parts, due to its superior mechanical properties; however, it has drawbacks such as aesthetic impairment, casting issues, stress shielding, and incompatibility with imaging techniques. These drawbacks have motivated researchers to find alternative materials such as polymers. Recently, the new polymeric material PEEK has a major role in most areas of dentistry, and therefore, it can represent an alternative biomaterial to overcome the drawbacks of titanium. The density of bone is expected to influence the choice of "All-on-four" materials. *Purpose*. This research applied finite-element investigations to evaluate the stresses on bone tissues and prosthetic parts in "All on four," utilizing three assemblies of materials, in normal and low bone densities. These assemblies were titanium (Type 1), titanium/PEEK (Type 2), and PEEK (Type 3). *Materials and Methods*. A 3D Mandibular model was constructed with a fixed prosthesis, and three assemblies of materials were stimulated, under 300 N unilateral force. The von Mises stresses were computed for the prosthetic parts and mucosa, while the maximum and minimum principal stresses/strains were computed for bone tissues due to their brittle and ductile properties. Moreover, the displacements of implants were extracted to check the prosthesis stability. *Results*. Type 2 and Type 3 minimized the stresses on frameworks, implants, abutments, and bone tissues, however, increased the mucosal stress, in comparison to Type 1. In the low-density model, Type 3 was recommended to reduce the stresses/strains on bone tissues and decrease the implant displacement, avoiding bone failure and increasing prosthesis stability. *Conclusions*. The bone density influenced the choice of "All-on-four" assembly. Moreover, further research on PEEK implants and abutments is required in the future.

1. Introduction

Implant-supported hybrid prostheses have lately been used to restore the quality of life of edentulous individuals. These prostheses eliminate the impact force of dynamic mastication on bone tissues, besides having a great performance and a good aesthetic appearance. The location of the mandibular canal and the anatomic limitations of the residual alveolar bone due to resorption make implant insertion challenging. In other cases, augmentation treatment of bone is also required. As a result, "All-on-four" technique has been employed to overcome these issues [1].

In the "All-on-four" technique, two anterior vertical implants and two tilted posterior implants are inserted into the jaw bone to decrease the cantilever length, increase the bone-implant contact area, increase the prosthesis stability, and reduce the bone stress. A solid framework is attached to the four implants to improve the stress distribution and alleviate the stresses on bone tissues and mucosa. Finally, the acrylic teeth are placed and fixed to the framework with acrylic material to construct the final fixed hybrid prosthesis [2, 3].

Protocol frameworks in "All-on-four" prostheses are usually made of titanium, due to its stiffness, durability, biocompatibility, and excellent mechanical properties. Some researchers have expected that stiff frameworks can resist deformation and transmit fewer stresses to the substructure parts (including the bone), protecting them [4, 5]. Nevertheless, contradictory results have been seen in studies evaluating the stresses transferred to the substructures by using stiff materials [6, 7]. Consequently, the soft frameworks have been recommended to be used to dampen the stresses transported to the substructure parts, protecting the bone tissues and increasing the prosthesis stability [6–8].

Soft polymers have recently been utilized in dentistry, in the production of crowns, bridges, orthodontic wires, partial and complete prostheses, and removable and fixed prostheses, among those, the new polymer (PEEK) [8–10]. This material has excellent biological, thermal, mechanical, and chemical properties. It is biocompatible, nontoxic, and radiolucent, besides having low elastic modulus (3.5 GPa) compared to titanium (110 MPa) and high shock-absorbing ability [8]. Hence, it is expected to dampen the stresses transferred to the substructures and the bone tissues, when utilized as a framework attached to the traditional titanium implants. The PEEK framework is anticipated to have several significant advantages over the titanium framework, including enhanced performance and aesthetics, greater design freedom, the ability to create lighter prostheses, lower overall system costs, reduced fabrication issues, and reduced risk of mechanical issues.

Other researchers have recommended the usage of PEEK material in the manufacture of implants and abutments not only the frameworks [11–13], to overcome the drawbacks of titanium which include aesthetic impairment, porosity, hypersensitivity, casting problem, and incompatibility with imaging techniques, besides, enhancing the distribution of masticatory forces around the implant. In the manufacture of implant, the titanium implant can cause a stress-shielding effect and, hence, implant loss, because of its high elastic modulus compared to the bone [4, 14, 15]. The limitations of titanium are also illustrated in the manufacture of abutments by hypersensitivity responses and the creation of biofilm [16]. However, there are few studies that have analyzed the stresses/strains produced in bone tissues and mucosa by utilizing the PEEK material in the manufacture of implants and abutments.

Implant geometry, surgical technique, and the quality of the surrounding bone have been expected to influence the primary stability of the fixed prostheses [17, 18]. Following tooth loss, bone loss is a common occurrence, affecting the mandible more frequently than the maxilla [19]. In the bone loss, bone resorption is faster than bone formation, lowering bone density and strength [20]. As a result, bone density is expected to influence the choice of materials assembly for "All-on-four" parts.

The finite-element method has a number of advantages over other approaches used in dentistry, including the ability to accurately depict complex geometries, apply model repair, and extract internal stresses/strains [21]. The aim of this study was to apply finite-element investigations to evaluate the stresses on bone tissues and prosthetic parts, using various assemblies of materials for "All-on-four" prosthesis, in normal and low bone densities, to choose the appropriate assembly for each bone condition and investigate the possibility of using PEEK as an alternative to titanium in the manufacture of frameworks only or all prosthetic parts. Three types of assemblies were used:

(i) Type 1: All prosthetic parts were from titanium. It was the traditional assembly.

(ii) Type 2: All prosthetic parts were from titanium, except the framework was from PEEK.

(iii) Type 3: All prosthetic parts were from PEEK.

2. Materials and Methods

2.1. Model Construction. A 3D model of a female mandible was downloaded from the "Grab-Cad" website (Grab-Cad Community [22]) with a height of 60 mm and length of 120 mm and saved as an STL file. The mandibular model exhibited severe bone resorption with 18 mm symphysis height as presented in Figure 1(a). Utilizing the software program Solid Works (Version 21, Massachusetts, USA), the model was converted to solid, modified, and repaired. The repair process included fixing the curves, gaps, missing faces, split, and extra edges, finding the edges that could be stitched and merging the very small faces. After that, the mandible was segmented into the cortical bone with 1.5 mm thickness and inner volume from the cancellous bone, with the mandibular ramus being predominantly cortical, as in previous studies [23–25]. Besides, the anterior and posterior parts of the mandible were covered with 2 mm mucosa, as shown in Figure 1(a) [26].

In the construction of the "All-on-four" prosthesis, first, four implants (ZIMMER, Biomet Dental, USA [27]) were modeled with the dimensions, as shown in Figure 1(b). The anterior implants were placed vertically in the lateral incisor region, while the posterior implants were placed at an angle of 30° in the second premolar region. All implants had perfect osseointegration and were positioned on the bone margin. Anterior implants were fitted with straight abutments, while posterior implants were fitted with angled abutments. Over the straight and angled abutments, titanium copings were installed to support the framework. The framework was designed with a horseshoe shape to follow the curvature of the mandible, with dimensions presented in Figure 1(c). Finally, 12 acrylic teeth were arranged on the framework and secured with the acrylic material, as illustrated in Figure 2.

Using Ansys software (ANSYS Workbench Version 18.0, Canonsburg, USA), the finite-element model was constructed with "adaptive" function and (0.4–2 mm) element size, based on the 10% convergence test. The final model had approximately 334,710 nodes and 200,032 elements.

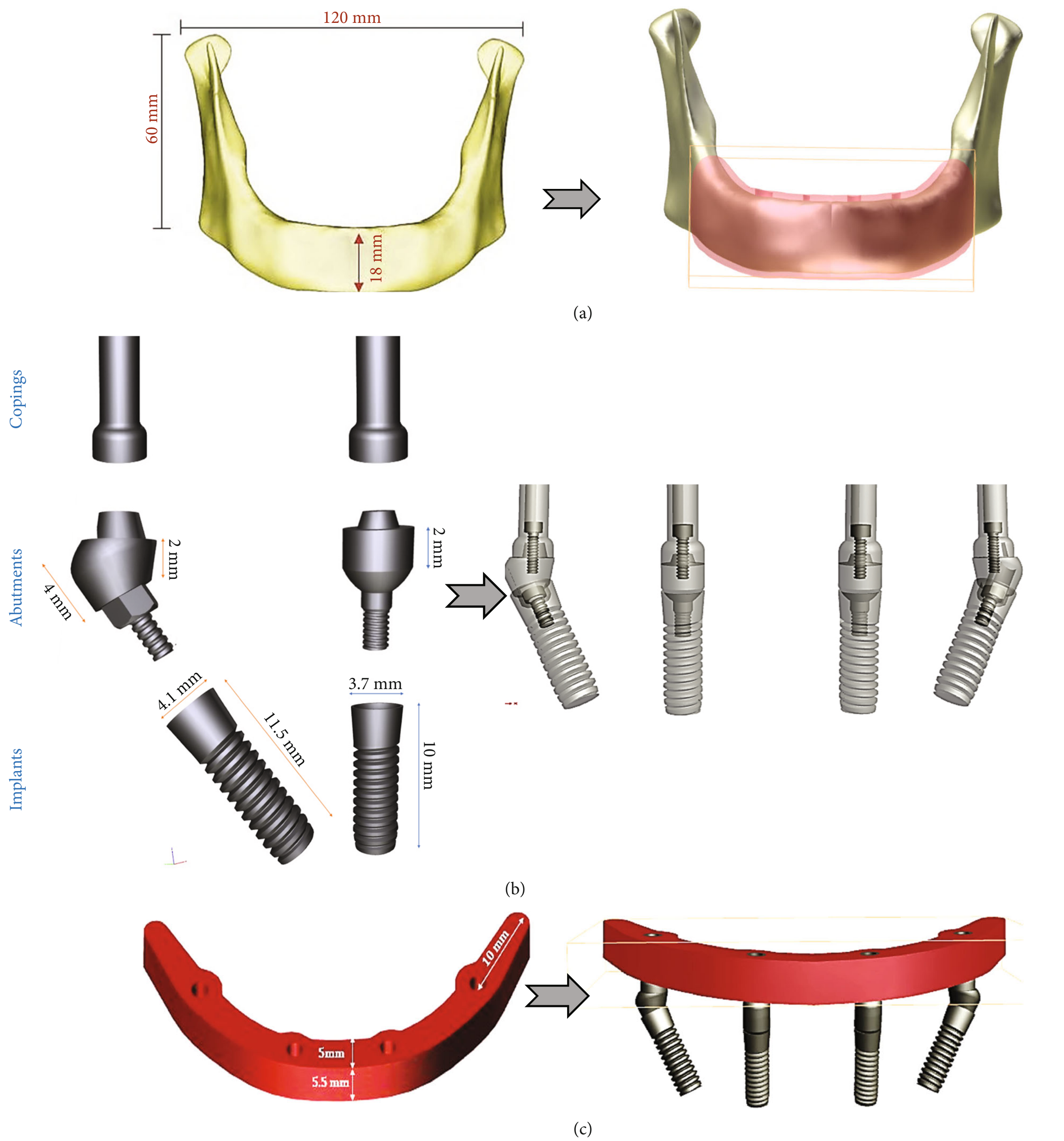


Figure 1: The construction of model parts. (a) Mandible bone & mucosa. (b) Implants, abutments and copings. (C) Framework in “All on four”.

2.2. Definition of Bone Density and Material Properties. The prosthetic parts (framework, implants, and abutments), in the “All–on-four” prosthesis, were stimulated with three assemblies of materials (as shown in Table 1). For reasons of simplification and time reduction, the mandible bone has been often stimulated with isotropic properties, especially when a complex model has been constructed [28]. The cortical bone density of the mandible ranged between 1200 and 1700 HU to represent the normal case and 950 HU to represent the low-density case [25, 29]. For the cancellous bone, the normal density ranged between 300 and 500 HU; hence, 150 HU was considered as a low-density case [25, 29]. The properties of all materials used in the finite-element model were illustrated in Table 2. The denture base and artificial teeth were made of acrylic PMMA.

2.3. Loading and Constraint Conditions. In fixed hybrid prosthesis, the average force ranged between 200 and 300 N in the first premolar and molar regions [35]. In this

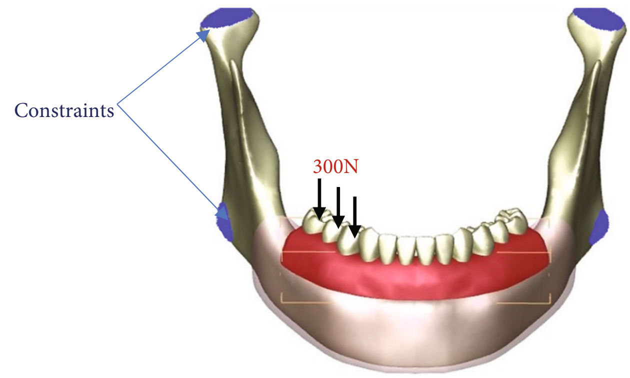


Figure 2: Final model (mandible with a fixed prosthesis) and load and constraint conditions.

Table 1: Three assemblies of materials for “All on four”.

	Implants	Abutments	Bar
Type 1 (control)	Titanium	Titanium	Titanium
Type 2	Titanium	Titanium	PEEK
Type 3	PEEK	PEEK	PEEK

study, 300 N force was applied to the three posterior teeth to stimulate the mechanism of unilateral mastication. Regarding the boundary conditions, the nodes of condyles and the inferior border of the mandible were constrained in all directions to prevent the displacement of the model under the force effect as illustrated in Figure 2 [36].

2.4. Analysis of Stresses and Strains. According to the von Mises Yield Criterion [37], the maximum von Mises stresses were extracted for all prosthetic parts (implants and abutments) in “All on four” and compared to the allowable stresses, due to their ductile properties (either made of titanium or PEEK). The allowable stresses of titanium and PEEK were nearly 900 and 140 MPa, respectively [8, 34].

For bone tissues, due to their ductile and brittle properties, the maximum (tensile) (P_{max}) and minimum (compressive) (P_{min}) principal stresses were extracted, and compared to the tensile and compressive strengths (Table 2), respectively, according to the failure theory of principal stress [37]. Moreover, the maximum and minimum principal strains were extracted for each bone tissue and compared with the critical limits. The concentration and the distribution of excessive strains might cause microdamage and induce bone resorption. The damage to cortical bone occurred when the strain exceeded 2500–3000 $\mu\varepsilon$ in tension and 5000 $\mu\varepsilon$ in compression [24, 25]. For the cancellous bone, the limits were 7000–8000 $\mu\varepsilon$ in tension and compression [38].

Additionally, in this research, the total displacements of implants were investigated and compared to the threshold (50 μm), to check the primary stability of the fixed prosthesis. Displacements more than 50 μm must be avoided due to the possibility of the production of fibrous tissues between the implant and the bone, decreasing the osseointegration [39, 40].

Table 2: Material properties used in the finite-element model.

	Elastic modulus (GPa)	Poisson ratio	Ref
Cortical bone			[24, 25, 30]
Normal density[a]	13.7	0.3	—
Low density [b]	4.14	0.3	—
Cancellous bone			[24, 25, 30, 31]
Normal density[c]	1.37	0.3	—
Low density[d]	0.259	0.3	—
Mucosa	0.005	0.4	[32]
PMMA	5	0.37	[33]
Titanium	110	0.35	[34]
PEEK	3.5	0.4	[8]

[a]Tensile strength = 90–170 MPa and compressive strength = 200 MPa. [b]Tensile strength = 70 MPa and compressive strength = 90 MPa. [c]Tensile strength = 10–20 MPa and compressive strength = 16–30 MPa. [d]Tensile strength = 3 MPa and compressive strength = 3.5 MPa.

3. Results

3.1. Stresses on Framework. For the two bone models, the lowest values of maximum von Mises stress on the framework were recorded in Type 2, followed by Types 3 and 1 (Figure 3). The stress value on titanium framework in Type 1 was (87.66 MPa), in the normal-density model. This value was reduced by 80.105 and 55.94% on PEEK frameworks of Types 2 and 3, respectively. In the low-density model, the stress value on the titanium framework was (78.3 MPa) and reduced by 80.1 and 53.48% on PEEK frameworks of Types 2 and 3.

3.2. Stresses on Implants. As illustrated in Figure 4, the lowest values of implant stress were observed in Type 3, followed by Types 2 and 1. In normal- and low-density models, the stresses on Type 2 implants were reduced by 2.55 and 4.57%, respectively, when compared to Type 1, while the stresses on Type 3 implants were significantly reduced by 49.62 and 59.4%. Moreover, the stresses on implants were observed to be higher in the low-density model than in the normal-density model.

3.3. Stresses on Abutments. In normal- and low-density models, the stresses on Type 1 abutments were 172.70 and 187.37 MPa, respectively. These values were reduced by 10.44 and 6.75% on Type 2 abutments and significantly reduced by 50.57 and 54% on Type 3 abutments, as shown in Figure 5. It also observed that the stresses on abutments in the low-density model were greater than those in the normal-density model.

3.4. Stresses on Mucosa. The highest values of mucosal stress were observed in Type 3, followed by Types 2 and 1, as

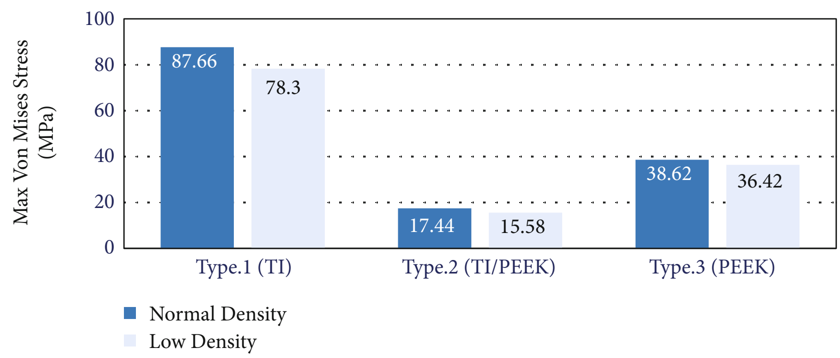


FIGURE 3: Maximum von Mises stresses (MPa) on the framework.

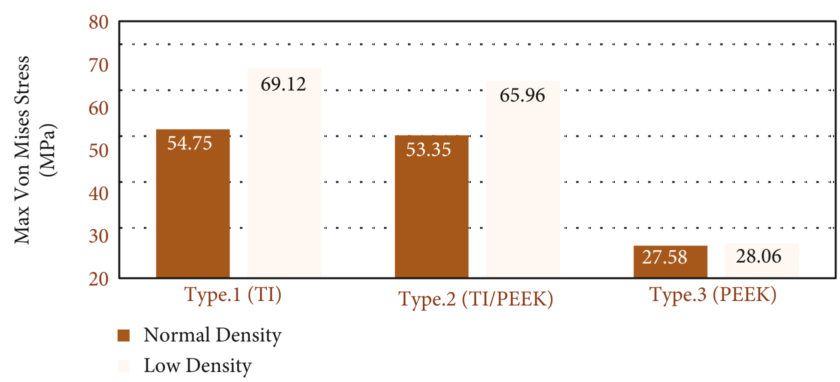


FIGURE 4: Maximum von Mises stresses (MPa) on implants.

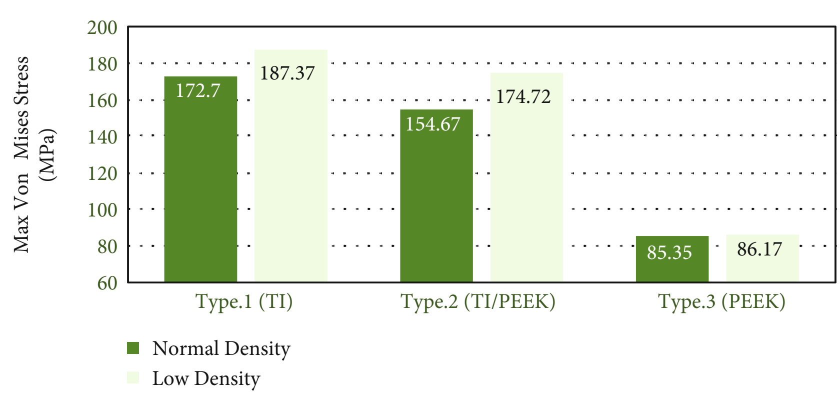


FIGURE 5: Maximum von Mises stresses (MPa) on abutments.

illustrated in Figure 6. The values of mucosal stress in the low-density model were higher than those in the normal-density model. In comparison to Type 1, the mucosal stress in Type 2 was increased by 43.056 and 9.12% in normal- and low-density models, respectively. In Type 3, the mucosal stress was nearly tripled in the normal-density model, while increased by 60.91% in the low-density model, compared to Type 1.

3.5. Stresses on Bone Tissues. Figures 7 and 8 illustrated the peak maximum and minimum principal stresses on cortical and cancellous bones, in normal- and low-density models. In the normal-density model, the maximum and minimum principal stresses on cortical bone were (21.05 and −43.42 MPa) by utilizing Type 1 prosthesis. These stresses were reduced by 3.7 and 1.45% and 62.56 and 33.835% by utilizing Types 2 and 3, respectively. For the cancellous bone, the peak maximum and minimum principal stresses were 3.43 and −5.16 MPa by utilizing Type 1 prosthesis, however, reduced by 6.414 and 6.39% and 56.26 and 42.44% by utilizing Types 2 and 3, respectively.

In the low-density model, the peak maximum and minimum principal stresses on the cortical bone were 20.28 and −33.69 MPa by utilizing Type 1, however, reduced by 3.3 and 4.42% and 72.28 and 38.17% by utilizing Types 2 and 3, respectively. In Type 1, the maximum and minimum principal stresses on the cancellous bone were 3.184 and −4.37 MPa. These stresses were

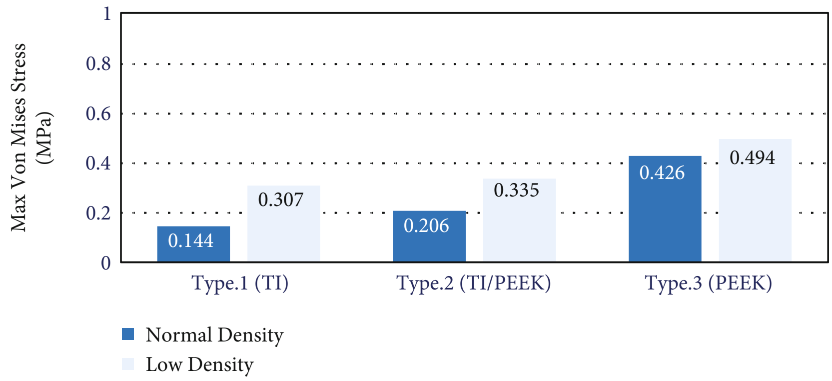


Figure 6: Maximum von Mises stresses (MPa) on mucosa.

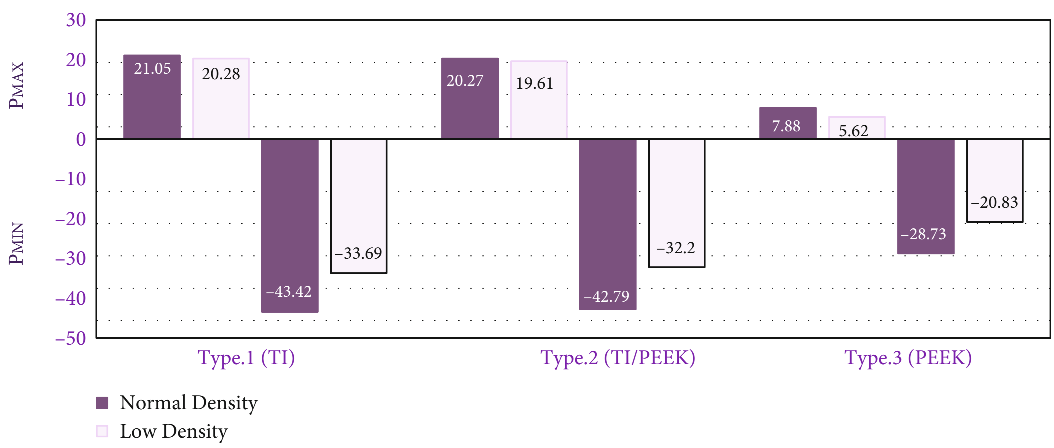


Figure 7: Maximum and minimum principal stresses (MPa) on cortical bone.

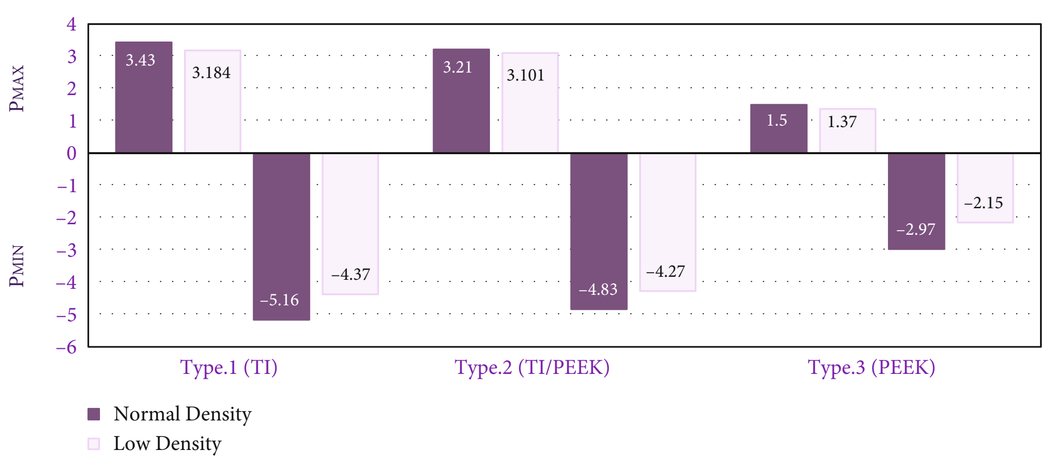


Figure 8: Maximum and minimum principal strains ($\mu\varepsilon$) on cortical bone.

reduced by 2.6 and 2.28% and 56.97 and 50.8% by utilizing Types 2 and 3, respectively. Figures 9 and 10 illustarted the distribution of maximum and minimum principal stresses on cortical and cancellous bones, in the low-density model.

3.6. Strains on Bone Tissues. The maximum and minimum principal strains for cortical and cancellous bones were also extracted in this research. Figures 11 and 12 showed that, in the two bone models using the three types, the cancellous bone exhibited larger strains than the cortical bone.

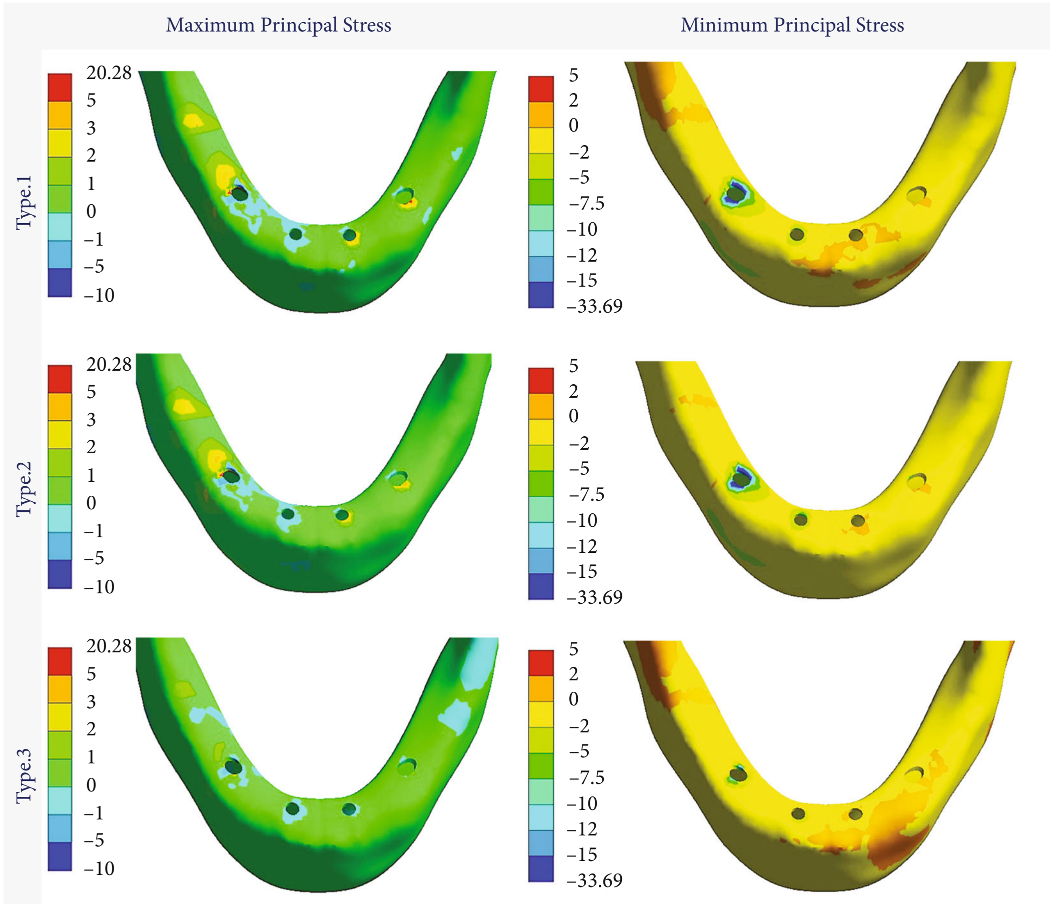


Figure 9: Maximum and minimum principal stresses (MPa) on cancellous bone.

Moreover, the strains of bone tissues had high values in the low-density model, in comparison to the normal-density model.

In the normal-density model, for cortical bone, the peak maximum and minimum principal strains were 1253 and −2392 $\mu\varepsilon$ in Type 1. These values were reduced by 3.35 and 1.29% using Type 2 and 35.11 and 22.9% using Type 3. For the cancellous bone, in Type 1, the maximum and minimum principal strains were 2279 and −3027 $\mu\varepsilon$, respectively. These values were reduced by 6.31 and 6.34% and 35.54 and 31.74% by using Types 2 and 3, respectively. In the low-density model, the peak maximum and minimum principal strains were 3935 and −6252 $\mu\varepsilon$ in Type 1, for the cortical bone. These strains were reduced by 3.25 and 2.22% using Type 2 and 50.67 and 28.9% using Type 3. For the cancellous bone, the maximum and minimum principal strains were 10,941 and −13,530 $\mu\varepsilon$ in Type 1. These strains were reduced by 2.59 and 2.26% and 44.43 and 50.02% by using Types 2 and 3, respectively.

3.7. Displacements of Implants. The total displacements (μm) of the four implants were extracted (Figure 13) and compared to the threshold (50 μm) to evaluate the primary stability of the fixed prosthesis. For all used types, implant 1 (loaded side) showed the highest displacement values, whereas implants 3 and 4 (nonloaded side) exhibited the lowest values. In addition, Type 3 had the lowest displacements (6.57 μm for implant 1, 1.76 μm for implant 2, 0.036 μm for implant 3, and 0.023 μm for implant 4) in the normal-density model and (19.68 μm for implant 1, 7.29 μm for implant 2, 1.64 μm for implant 3, and 1.21 μm for implant 4) in the low-density model.

4. Discussion

This paper conducted finite-element investigations to explore the influence of utilizing the PEEK material as an alternative to titanium, in the manufacture of frameworks only, or both frameworks, implants, and abutments. Three assemblies in "All on four" were stimulated and the stresses transferred to the prosthetic parts and the surrounding bone tissues were evaluated, using varied densities of the cortical and cancellous bones. The assemblies utilized in "All on four" were titanium as a control (Type 1), titanium/PEEK (Type 2), and PEEK (Type 3).

The maximum von Mises stresses were extracted for all prosthetic parts (frameworks, implants, and abutments), due to their ductile properties (either made of titanium or PEEK), according to the von Mises Yield Criterion [37] and studies [6, 9, 36, 40–42]. For cortical and cancellous bones, the maximum (tensile) and minimum (compressive) principal stresses were extracted and compared to the

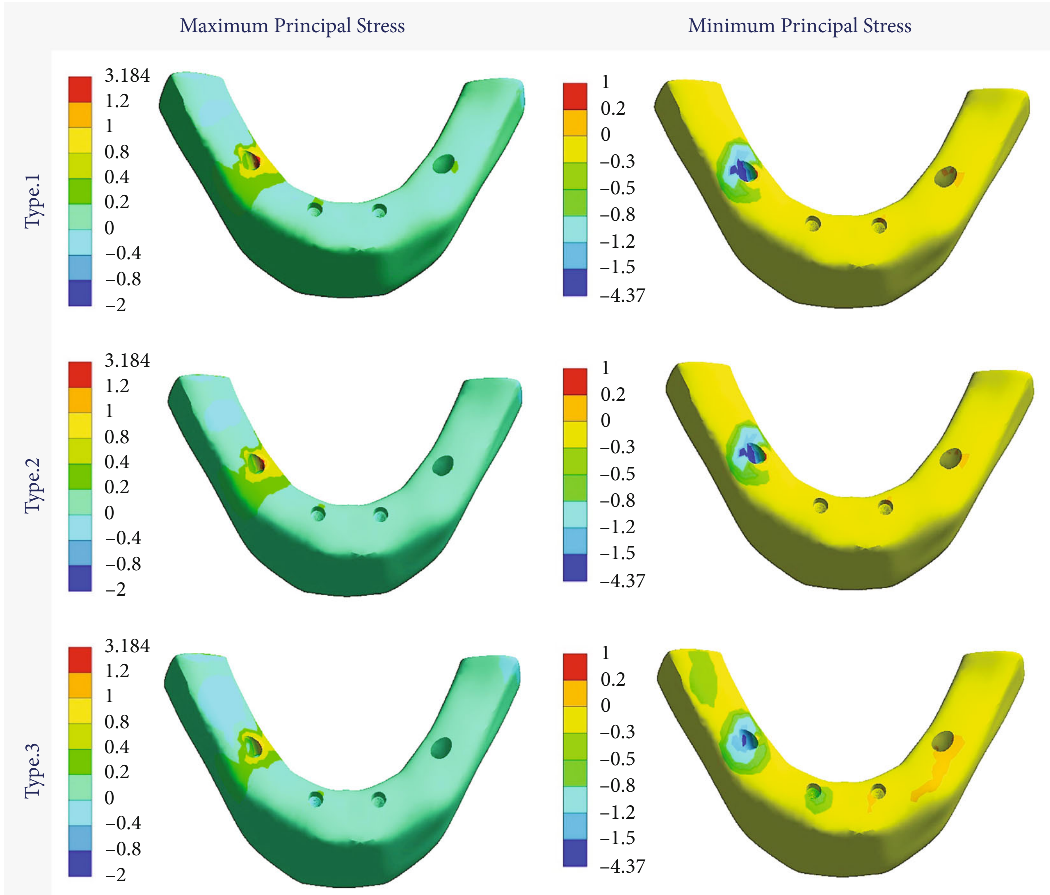


Figure 10: Maximum and minimum principal strains ($\mu\varepsilon$) on cancellous bone.

allowable tensile and compressive stresses (Table 2), according to the failure theory of principal stress [37] and like most studies [6, 43, 44], to investigate the yielding/failure behavior of each bone tissue. In addition, for cortical and cancellous bones, the maximum and minimum principal strains were taken into account and compared with the critical physiological limits, as recommended by previous studies [5, 24, 25, 45]. As excessive strain might cause damage to the implant–bone interfaces and the microstructure of the bone, causing a loss of osseointegration with the implants and inducing bone resorption.

To stimulate the unilateral mastication mechanism, a 300 N vertical force was distributed on the three posterior teeth. As a result, the tensile and compressive stresses on the cortical and cancellous bones were concentrated around the loaded posterior holes, as FEA studies [5, 6, 11, 24, 25, 36, 39, 41]. Figures 11 and 12 illustrated also that Type 3 reduced the concentrations of the tensile and compressive stresses around the loaded holes in cortical and cancellous bones, compared to Types 1 and 2.

In the fabrication of frameworks, titanium has frequently been employed, because of its biocompatibility, stiffness, durability, and superior mechanical properties. Since stiff frameworks can resist the deformation and reduce the stresses transferred to the substructure parts, preventing prosthesis failure [4, 5]. Other studies have recommended the usage of soft materials in the fabrication of frameworks, due to their shock-absorbing ability, to dampen the stresses transferred to bone tissues [6–8]. The new soft polymeric material PEEK has recently been used in dentistry in place of metallic and ceramic materials. This material is nontoxic, nonallergic, radiolucent, and biocompatible with excellent thermal stability, low plaque affinity, and good biological, mechanical, and chemical properties [8–10].

In this paper, the PEEK framework was utilized (Type 2) instead of titanium (Type 1), and attached to the four titanium abutments of implants. In the two bone models, the results illustrated that the PEEK framework reduced the stresses on implants and abutments, compared to the titanium framework, however, increased the stresses on the mucosa. Additionally, the stresses and strains on cortical and cancellous bones were reduced. These findings were in close agreement with the studies [6, 7, 46, 47]. In Shash et al. research [46], a mandibular model with a fixed prosthesis was constructed with titanium implants and abutments, and then the framework was stimulated with different materials, among them the PEEK. The results clarified that the PEEK framework reduced the stresses on cortical and cancellous bones by 3.44 and 3%, compared to titanium. In Haroun et al. research [6], the tensile and compressive stresses on maxilla rehabilitated with a fixed prosthesis and zirconium superstructure were evaluated using

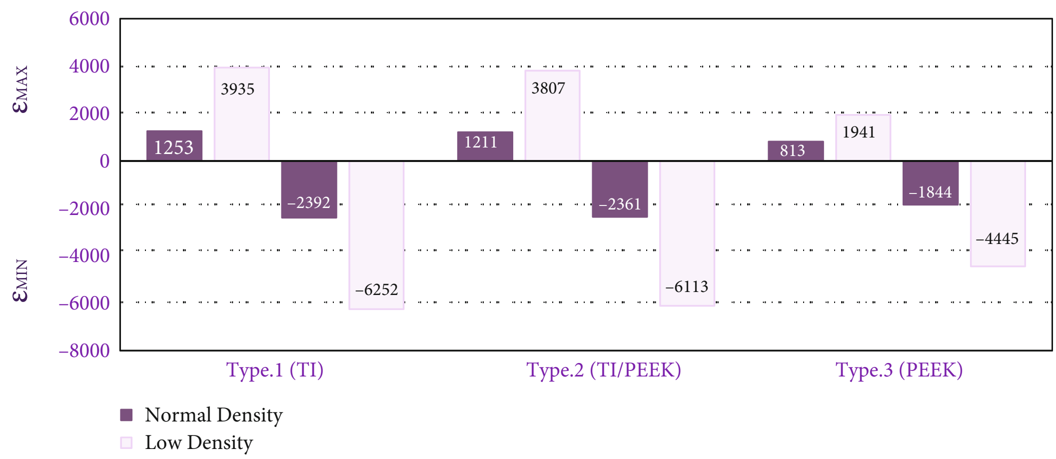


Figure 11: The distribution of maximum and minimum principal stresses (MPa) on cortical bone, in the low-density model.

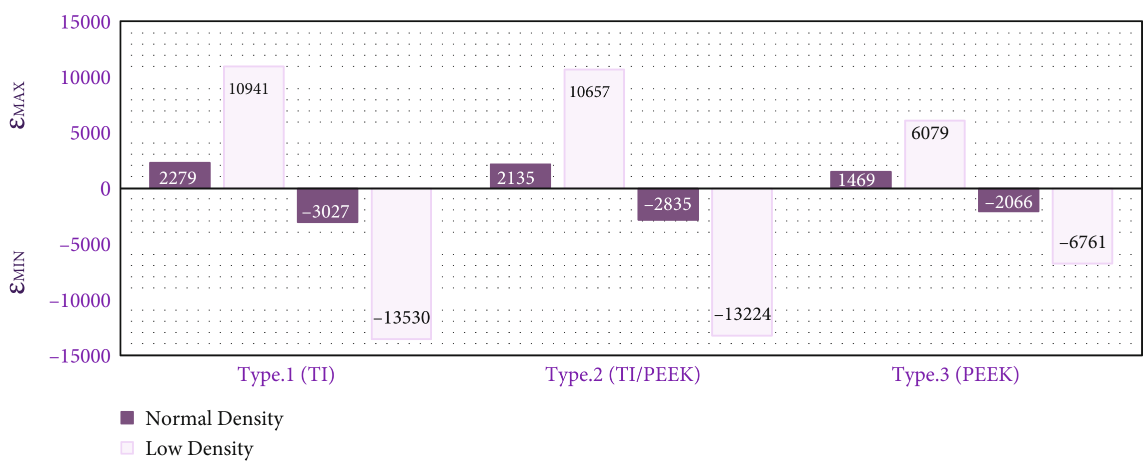


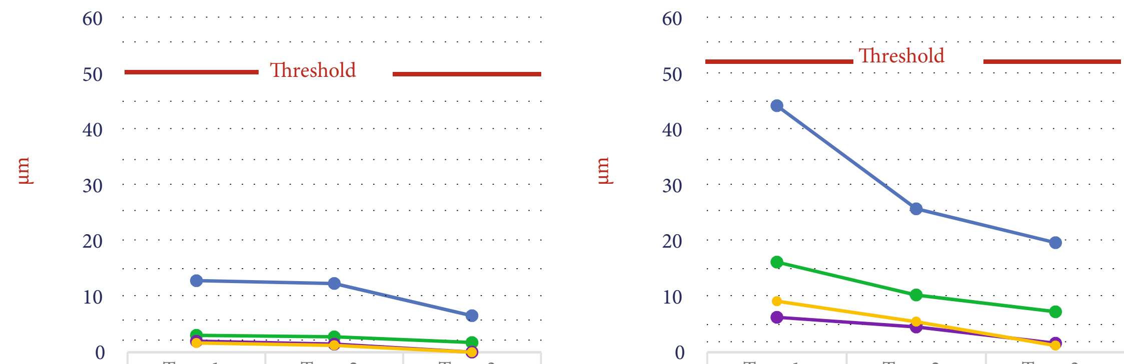
Figure 12: The distribution of maximum and minimum principal stresses (MPa) on cancellous bone, in the low-density model.

the PEEK framework in place of titanium. The results illustrated that the PEEK framework reduced the tensile and compressive stresses on the bone by 32.3 and 41.9% when the load was delivered from the opposing acrylic "All-on-four" prosthesis.

Chen et al. [7] conducted finite-element assessments of the mechanical performance of four designs of removable partial dentures, by employing three framework materials (cobalt chrome, titanium alloy, and PEEK). The results showed that, when compared to cobalt chrome and titanium, the PEEK framework produced the lowest stress on the framework, the lowest stress on periodontal ligament, and the highest mucosal stress. According to Sinha et al. case report [47], using PEEK as a framework for a fixed partial denture (FPD) led to extremely excellent results with a high level of patient comfort and acceptability because of its lightweight. The researchers believed that the PEEK material will play a major role in the fabrication of FPD frameworks in near future and will have a long-lasting impact on the aesthetics and functional potential of patients using this material for oral rehabilitation.

In implantology, titanium has been frequently used because of its excellent mechanical qualities. Despite the benefits of titanium, there were certain drawbacks, including aesthetic impairment, hypersensitivity, allergic reactions, casting problems, metallic tastes, incompatibility with imaging techniques, and peri–implantitis-related surface corrosion. Furthermore, the difference in elastic modulus between bone (14 GPa) and titanium (110 GPa) induced a stress-shielding effect, resulting in bone overloading, bone resorption, and thus a serious problem with implant stability [14, 15, 48, 49]. These drawbacks, according to researchers, could be mitigated by the use of PEEK implants [8, 11, 12, 50].

In the manufacture of abutments, a variety of metallic and ceramic materials, such as titanium and zirconia, have been utilized. The material of the abutment should produce less biofilm accumulation on its surface since the surface of the abutment is extremely vulnerable to subgingival biofilm production. The limitations of metals were represented in the hypersensitivity responses and the formation of biofilm [4, 14, 16]. While the limitations of zirconia were represented in its high cost, high elastic modulus, and density [51]. PEEK abutments have good properties and they have been expected to produce less biofilm accumulation [8, 13]. As a result, the PEEK material could be a viable alternative to titanium in the manufacture of abutments.



	Type.1	Type.2	Type.3
Imp.1	12.87	12.36	6.57
Imp.2	3.06	2.78	1.76
Imp.3	2	1.47	0.036
Imp.4	1.68	1.26	0.023

(a)

	Type.1	Type.2	Type.3
Imp.1	44.28	25.78	19.68
Imp.2	16.21	10.3	7.29
Imp.3	6.29	4.56	1.64
Imp.4	9.18	5.5	1.21

(b)

Figure 13: Displacement (μm) of the implants. (a) Normal-density model. (b) Low-density model.

This paper also conducted another study to investigate the possibility of using PEEK in the manufacture of implants and abutments (Type 3), not just the framework, to overcome the drawbacks of titanium and construct high-performance metal-free prostheses. From comparing Type 3 with Type 2, the results demonstrated that the use of PEEK material in the stimulation of implants and abutments (beneath the PEEK framework) resulted in decreases in their stresses as well as the stresses/strains on the surrounding bone tissues. This caused increases in the stresses on the framework and mucosa. The results illustrated also that, in Type 3, significant reductions were observed in the stresses on the framework, implants, and abutments, when compared to Type 1. Consequently, the stresses and strains on both cancellous and cortical bones were reduced, in the cases of normal and low densities. The drawback of using Type 3 prosthesis was that the values of mucosal stress were extremely increased. However, these values were lower than the pain threshold (0.62–1.2 MPa [52]), and hence, no pain might occur. These results closely matched the findings of the following studies [9, 41, 53, 54].

In Mohammed's thesis [41], PEEK implants were used in place of titanium in an overdenture mandibular prosthesis, and the distributions of bone stresses were evaluated. The results illustrated that the PEEK implants decreased the maximum von Mises stresses on cortical and cancellous bones by 13 and 46%, respectively, however, increased the stress on the mucosa. Another study [53] compared the stress distribution and deformation in the bone surrounding the implant, using three implant materials (titanium, zirconia, and PEEK), under vertical and oblique forces. The results demonstrated that the PEEK material could be used as an alternative to titanium in the manufacture of implants.

In the manufacture of abutments, Tekin et al. [9], evaluated the stress generated in the peri–implant bone by using PEEK abutment as an alternative to titanium, beneath the PEEK crown. The results demonstrated that PEEK abutment caused a reduction of 1.1% on the maximum von Mises stress on the bone, compared to titanium, Furthermore, Korsel [54] conducted a 3D finite-element investigation to evaluate the stress distributions in implants, screws, and bone, employing various abutment materials, among them the modified PEEK (BIOHPP). The result showed that BIOHPP abutment decreased the stresses on the implant and bone by 10.9 and 15%, however, increased the stress on the screw. Subsequently, further research and long-term studies on PEEK implants and abutments are required in near future.

The impact of bone density on the choice of the assembly of materials for "All-on-four" prosthesis was also investigated in this work. The findings showed that the stresses generated on all parts, particularly the mucosa, cancellous, and cortical bones, were influenced by bone density. In the low-density model, the stresses on cancellous and cortical bones were reduced, compared to the normal-density model. As a result, the stresses on implants, abutments, and mucosa were increased. Additionally, the low-density model showed higher maximum and minimum principal strains on cortical and cancellous bones than that of the normal-density model. This was consistent with Mehhoob et al. [55] and Ouldyerou et al. [49] studies, which demonstrated that strains in the osteoporotic bone were higher than in the healthy bone.

From the evaluation of the results, the maximum von Mises stresses generated on all prosthetic parts (titanium or PEEK), in Types 1, 2, and 3 did not exceed the allowable stresses (900 MPa for titanium and 140 MPa for PEEK) in the two bone models, reducing the possibility of mechanical failures. For cortical and cancellous bones, in the normal-density model, the stresses and strains did not surpass the critical limits, by using Types 1, 2, and 3. In the low-density model, the stresses and strains on cancellous bone as well as the strains on cortical bone exceeded the allowable limits, by using Types 1 and 2, and hence, failure in bone tissues might occur. Consequently, Type 3 was preferred to be used in this case to reduce the stresses and strains generated on different bone tissues, preventing bone failure and increasing prosthesis stability.

The displacements of implants were also computed in this study using Types 1, 2, and 3 and compared to the threshold (50 μm), to evaluate the primary stability of the prosthesis. Due to the possibility of fibrous tissue forming between the implant and the bone, displacements higher than 50 μm must be avoided [39, 40]. According to the results, in the normal-density model, all implants showed displacements that were less than 50 μm, demonstrating the prosthesis stability. In the low-density model, by utilizing Type 1, the loaded implant (implant 1) exhibited displacement close to 50 μm. However, by utilizing Types 2 and 3, implant 1 exhibited displacement less than 50 μm.

5. Conclusion

Within the limitations of this study, the following were concluded:

(i) In comparison to Types 1, 2, and 3 reduced the stresses on frameworks, implants, abutments, and bone tissues.

(ii) The usage of PEEK in the stimulation of all "All-on-four" parts resulted in significant reductions in the stresses and strains generated on cortical and cancellous bones, however, increased the mucosal stress.

(iii) In the low-density model, Type 3 was recommended to be used to reduce the stresses and strains generated on different bone tissues and reduce the displacement of implants, preventing bone failure and enhancing the prosthesis performance.

(iv) Further research and many controlled clinical trials on PEEK implants and abutments are required in near future.

Data Availability

The data used to support the findings of this study are included within the article.

Ethical Approval

The conducted research is not related to either human or animals use.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] A. Kutkut, E. Bertoli, R. Frazer, G. Pinto-Sinai, R. Fuentealba Hidalgo, and J. Studts, "A systematic review of studies comparing conventional complete denture and implant retained overdenture," *Journal of Prosthodontic Research*, vol. 62, no. 1, pp. 1–9, 2018.

[2] S. Patzelt, O. Bahat, M. Reynolds, and J. Strub, "The all-on-four treatment concept: a systematic review," *Clinical Implant Dentistry and Related Research*, vol. 16, no. 6, pp. 836–855, 2014.

[3] F. Egilmez, G. Ergun, I. Cekic-Nagas, and S. Bozkaya, "Implant-supported hybrid prosthesis: conventional treatment method for borderline cases," *European Journal of Dentistry*, vol. 9, no. 3, pp. 442–448, 2015.

[4] S. Tharani, S. Prasanna, C. Krithika, and R. Raghavan, "Review of metallic biomaterials in dental applications," *Journal of Pharmacy & Bioallied Sciences*, pp. 14–19, 2020.

[5] S. Horita, T. Sugiura, K. Yamamoto, K. Murakami, Y. Imai, and T. Kirita, "Biomechanical analysis of immediately loaded implants according to the "All- on-Four" concept," *Journal of Prosthodontic Research*, vol. 61, no. 2, pp. 123–132, 2017.

[6] F. Haroun and O. Ozan, "Evaluation of stresses on implant, bone, and restorative materials caused by different opposing arch materials in hybrid prosthetic restorations using the all-on-4 technique," *Materials*, vol. 14, no. 15, p. 4308, 2021.

[7] X. Chen, B. Mao, Z. Zhu et al., "A three-dimensional finite element analysis of mechanical function for 4 removable partial denture designs with 3 framework materials: CoCr, Ti-6Al-4V alloy and PEEK," *Scientific Reports*, vol. 9, no. 1, p. 13975, 2019.

[8] S. Tekin, S. Cangül, O. Adıgüzel, and Y. Değer, "Areas for use of PEEK material in dentistry," *International Dental Research*, vol. 8, no. 2, pp. 84–92, 2018.

[9] S. Tekin, Y. Değer, and F. Demirci, "Evaluation of the use of PEEK material in implant-supported fixed restorations by finite element analysis," *Nigerian Journal of Clinical Practice*, vol. 22, no. 9, pp. 1252–1258, 2019.

[10] F. Rahmitasari, Y. Ishida, K. Kurahashi, T. Matsuda, M. Watanabe, and T. Ichikawa, "PEEK with reinforced materials and modifications for dental implant applications," *Dentistry Journal*, vol. 5, no. 4, p. 35, 2017.

[11] A. Schwitalla, M. Abou-Emara, T. Spintig, J. Lackmann, and W. Müller, "Finite element analysis of the biomechanical effects of PEEK dental implants on the peri-implant bone," *Journal of Biomechanics*, vol. 48, no. 1, pp. 1–7, 2015.

[12] A. Schwitalla and W. D. Müller, "PEEK dental implants: a review of the literature," *The Journal of Oral and Implantology*, vol. 39, no. 6, pp. 743–749, 2013.

[13] M. Al-Rabab'ah, W. Hamadneh, I. Alsalem, A. Khraisat, and K. A. Abu, "Use of high performance polymers as dental implant abutments and frameworks: a case series report," *Journal of Prosthodontics*, vol. 28, no. 4, pp. 365–372, 2019.

[14] K. T. Kim, M. Y. Eo, T. T. H. Nguyen, and S. M. Kim, "General review of titanium toxicity," *International Journal of Implant Dentistry*, vol. 5, no. 1, p. 10, 2019.

[15] K. Prasad, O. Bazaka, M. Chua et al., "Metallic biomaterials: current challenges and opportunities," *Materials*, vol. 10, no. 8, p. 884, 2017.

[16] S. Hahnel, A. Wieser, R. Lang, and M. Rosentritt, "Biofilm formation on the surface of modern implant abutment materials," *Clinical Oral Implants Research*, vol. 26, no. 11, pp. 1297–1301, 2015.

[17] H. Bilhan, O. Geckili, E. Mumcu, E. Bozdag, E. Sünbüloğlu, and O. Kutay, "Influence of surgical technique, implant shape and diameter on the primary stability in cancellous bone," *Journal of Oral Rehabilitation*, vol. 37, no. 12, pp. 900–907, 2010.

[18] R. Alaqeely, N. Babay, and M. AlQutub, "Dental implant primary stability in different regions of the Jawbone: CBCT-based 3D finite element analysis," *Saudi Dent Journal*, vol. 32, no. 2, pp. 101–107, 2020.

[19] C. Ledesma, M. Jimenez-Farfan, and J. Hernandez, "Idiopathic osteosclerosis in the maxillomandibular area," *La Radiologia Medica*, 2018.

[20] N. M. Appelman-Dijkstra and S. E. Papapoulos, "Modulating bone resorption and bone formation in opposite directions in the treatment of postmenopausal osteoporosis," *Drugs*, vol. 75, no. 10, pp. 1049–1058, 2015.

[21] S. Trivedi, "Finite element analysis: a boon to dentistry," *Journal of Oral Biology and Craniofacial Research*, vol. 4, no. 3, pp. 200–203, 2014.

[22] Grab CAD, "Community. Making additive manufacturing at scale possible: library," updated (9/2021). https://grabcad.com/library.

[23] J. E. Lim, W. H. Lim, and Y. S. Chun, "Cortical bone thickness and root proximity at mandibular interradicular sites: implications for orthodontic mini-implant placement," *Orthodontics & Craniofacial Research*, vol. 38, no. 6, pp. 397–406, 2008.

[24] T. Sugiura, K. Yamamoto, M. Kawakami, S. Horita, K. Murakami, and T. Kirita, "Influence of bone parameters on peri-implant bone strain distribution in the posterior mandible," *Medicina Oral Patología Oral y Cirugía Buccal*, vol. 20, no. 1, 2015.

[25] S. Horita, T. Sugiura, K. Yamamoto, K. Murakami, S. Tsutsumi, and T. Kirita, "The effects of bone density and crestal cortical bone thickness on micromotion and peri-implant bone strain distribution in an immediately loaded implant: a nonlinear finite element analysis," *Journal of Periodontal and Implant Science*, vol. 3, pp. 152–165, 2016.

[26] M. Munakata, K. Nagata, M. Sanda, R. Kawamata, D. Sato, and K. Yamaguchi, "Variations in vertical mucosal thickness at edentulous ridge according to site and gender measured by cone-beam computed tomography," *International Journal of Implant Dentistry*, vol. 7, no. 1, p. 34, 2021.

[27] Zimmer Biomet Dental, "Product catalog," http://www.zimmerbiometdental.com/en.

[28] A. S. Bonnet, M. Postaire, and P. Lipinski, "Biomechanical study of mandible bone supporting a four-implant retained bridge: finite element analysis of the influence of bone anisotropy and foodstuff position," *Medical Engineering & Physics*, vol. 31, no. 7, pp. 806–815, 2009.

[29] H. S. Park, Y. J. Lee, S. H. Jeong, and T. G. Kwon, "Density of the alveolar and basal bones of the maxilla and the mandible," *American Journal of Orthodontics and Dentofacial Orthopedics*, vol. 133, no. 1, pp. 30–37, 2008.

[30] S. Schickert, J. Beucken, S. Leeuwenburgh, and J. Jansen, "Preclinical evaluation of biological bone substitute materials for application in highly loaded skeletal sites," *Biomolecules*, vol. 10, no. 6, 2020.

[31] R. Resnik, "Misch's contemporary implant dentistry," *Elsevier - Health Sciences Division*, pp. 830–850, 2019.

[32] K. Sadr, J. Alipour, and F. Heidary, "Finite element analysis of soft-lined mandibular complete denture and its supporting structures," *Journal of Dental Research, Dental Clinics, Dental Prospects*, vol. 6, no. 2, pp. 37–41, 2012.

[33] M. S. Zafar and N. Ahmed, "Nanoindentation and surface roughness profilometry of poly methyl methacrylate denture base materials," *Technology and Health Care*, vol. 22, no. 4, pp. 573–581, 2014.

[34] AZO Materials, "Titanium alloys—Ti6Al4V grade 5," https://www.azom.com/properties.aspx?ArticleID=1547.

[35] M. A. Pérez, "Life prediction of different commercial dental implants as influence by uncertainties in their fatigue material properties and loading conditions," *Computer Methods and Programs in Biomedicine*, vol. 108, no. 3, pp. 1277–1286, 2012.

[36] F. A. Hussein, K. N. Salloomi, B. Y. Abdulrahman, A. R. Al-Zahawi, and L. A. Sabri, "Effect of thread depth and implant shape on stress distribution in anterior and posterior regions of mandible bone: a finite element analysis," *Dental Research Journal*, vol. 16, no. 3, pp. 200–207, 2019.

[37] R. M. Christensen, *The Theory of Materials Failure*, OUP Oxford, 2013.

[38] G. Limbert, C. van Lierde, O. L. Muraru et al., "Trabecular bone strains around a dental implant and associated micromotions—A micro-CT-based three-dimensional finite element study," *Journal of Biomechanics*, vol. 43, no. 7, pp. 1251–1261, 2010.

[39] M. B. Ferreira, V. A. Barão, J. A. Delben, L. P. Faverani, A. C. Hipólito, and W. G. Assunção, "Non-linear 3D finite element analysis of full-arch implant-supported fixed dentures," *Materials Science & Engineering C, Materials for Biological Applications*, vol. 38, pp. 306–314, 2014.

[40] A. H. Sadr Haghighi, V. Pouyafar, A. Navid, M. Eskandarinezhad, and T. Abdollahzadeh Baghaei, "Investigation of the optimal design of orthodontic mini-implants based on the primary stability: a finite element analysis," *Journal of Dental Research, Dental Clinics, Dental Prospects*, vol. 13, no. 2, pp. 85–89, 2019.

[41] M. Mohammed, "Stress distribution in mandibular over denture supported by four mini implants versus two conventional implants," Faculty of Dentistry, Minia University, 2016, Unpublished Master Thesis.

[42] K. Kelkar, V. Bhat, and C. Hegde, "Finite element analysis of the effect of framework materials at the bone-implant interface in the all-on-four implant system," *Dental Research Journal*, vol. 18, no. 1, 2021.

[43] J. Park, S. Ahn, H. Lee, and G. Noh, "Implant placement in the removable mandibular advancement device for completely edentulous patients: a finite element study," *Journal of Computational Design and Engineering*, vol. 8, no. 1, pp. 140–148, 2021.

[44] N. Türker, U. S. Büyükkaplan, S. J. Sadowsky, and M. M. Özarslan, "Finite element stress analysis of applied forces to implants and supporting tissues using the "All-on-Four" concept with different occlusal schemes," *Journal of Prosthodontics*, vol. 28, no. 2, pp. 185–194, 2019.

[45] S. Nemati and S. Khorramymehr, "Three-dimensional evaluation of a dental implant in different angles by finite element method," *Journal of Bioengineering Research*, vol. 1, no. 1, pp. 42–53, 2019.

[46] Y. H. Shash, M. M. Dohiem, M. T. Elwakad, and M. A. Eldosoky, "Effect of bar material on the biomechanical performance of hybrid dental prosthesis," *2021 3rd Novel Intelligent and Leading Emerging Sciences Conference (NILES)*, pp. 37–40, 2021.

[47] N. Sinha, N. Gupta, K. M. Reddy, and Y. M. Shastry, "Versatility of PEEK as a fixed partial denture framework," *The Journal of the Indian Prosthodontic Society*, vol. 17, no. 1, pp. 80–83, 2017.

[48] J. Li, J. A. Jansen, X. F. Walboomers, and J. J. van den Beucken, "Mechanical aspects of dental implants and osseointegration: a

narrative review," *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 103, p. 103574, 2020.

[49] A. Ouldyerou, L. Aminallah, A. Merdji, A. Mehboob, and H. Mehboob, "Finite element analyses of porous dental implant designs based on 3D printing concept to evaluate biomechanical behaviors of healthy and osteoporotic bones," *Mechanics of Advanced Materials and Structures*, pp. 1–13, 2022.

[50] H. S. Alghamdi and J. A. Jansen, "The development and future of dental implants," *Dental Materials Journal*, vol. 39, no. 2, pp. 167–172, 2020.

[51] Z. F. Chen, P. H. Nang, Y. Wang, and Z. B. Luo, "Clinical evaluation of ceramic implant abutments in anterior restorations," *Annals of the Royal Australasian College of Dental Surgeons*, vol. 19, pp. 67–70, 2008.

[52] T. Ogawa, M. Tanaka, T. Ogimoto, N. Okushi, K. Koyano, and K. Takeuchi, "Mapping, profiling and clustering of pressure pain threshold (PPT) in edentulous oral mucosa," *Journal of Dentistry*, vol. 32, no. 3, pp. 219–228, 2004.

[53] S. A. Haseeb, K. C. Vinaya, N. Vijaykumar, A. S. Durga, A. S. Kumar, and M. K. Sruthi, "A 3D finite element analysis to compare stress distribution and deformation in bone using titanium, zirconia and peek implant biomaterials," *Oral Health and Dental Management*, vol. 20, p. 355, 2021.

[54] A. Korsel, "3D finite element stress analysis of different abutment materials in screw, implant and cortical bone," *Egyptian Dental Journal*, vol. 66, no. 1, pp. 415–421, 2020.

[55] H. Mehboob, A. Mehboob, F. Abbassi, F. Ahmad, A. S. Khan, and S. Miran, "Bioinspired porous dental implants using the concept of 3D printing to investigate the effect of implant type and porosity on patient's bone condition," *Mechanics of Advanced Materials and Structures*, pp. 1–15, 2021.