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Stress behavior of an anterior single implant restored with high performance polymer abutments under immediate and delayed loading: A 3D FEA study

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Abstract:	Purpose: To evaluate the stress generated on peripheral bone, implant, and prosthetic components while using polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) hybrid abutments in two different loading situations with nonlinear three-dimensional finite element analysis. Materials and Methods: Standard tessellation language (STL) files of original components were used for the in-silico modeling of implant, standard titanium abutment, and hybrid abutments (PEEK and PEKK). The implant was placed in the bone block to imitate immediate loading, in which a friction coefficient of 0.3 was set between the bone and the implant interface, or delayed loading, where the bone-implant interface was assumed to be perfect. In all models, both a horizontal force (25.5 N) and a 30-degree oblique force (178 N) were applied to the long axis of the implant to the palatal surface of the restoration. The stress distribution was evaluated. Results: While more stress was observed in the prosthetic structures in the PEEK and PEKK models, the stresses on the implant and bone were similar in all models, regardless of the loading situation. Under immediate loading, PEEK hybrid abutments caused excessive stress accumulation on the titanium base abutment. Conclusions: Even though abutment type did not affect the stresses on peripheral bone, PEEK and PEKK abutments generated greater stresses on the implant and the standard titanium abutment accumulated higher stresses. Oblique forces mostly generated greater stress than horizontal forces. Oblique forces on immediately loaded implant led to stresses higher than the yield strength of a titanium implant when restored with PEEK hybrid abutment.

ABSTRACT

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Keywords: finite element analysis, polyetheretherketone, polyetherketoneketone, implant abutment

Dental implants stand out as a suitable treatment option for the rehabilitation of partially or completely edentulous patients.[1,2] Titanium has been considered as the gold standard material for implant abutments.[3] However, the tendency towards tooth-colored materials has increased, particularly in cases where patient has a high smile line and the gray color of titanium negatively affects esthetics.[4] High-performance polymers such as polyetheretherketone (PEEK) and polyetherketonketone (PEKK) have been utilized in medicine and dentistry.[5] These polymers have shock absorption capability, and elastic modulus similar to bone, besides having tooth-like color.[6] Thus, they can reduce the stress transmitted to peripheral tissues and bone.[7] Since PEKK contains more ketone groups than PEEK, it has higher compressive strength and a closer elastic modulus to bone.[8]

One of the critical factors in the success of dental implants is the transfer of oblique, lateral, and vertical loads that occur during chewing as they cause stress on implant components and peripheral tissues.[9] Depending on the prosthetic design and restorative materials, the uneven distribution of stress can lead to resorption at the bone-implant interface and eventually implant loss.[5,10] Finite element analysis (FEA), which can be performed either as linear or nonlinear, is a successful method for determining the stress and strains on dental implants and surrounding tissues that are generated by the forces in the oral environment.[11, 12] Nonlinear FEA provides more detailed information and nonlinearities can be categorized as geometric, material, and contact nonlinearity. Among these principal groups, contact nonlinearity defines a structural behavior, which can be seen between the implant and the prosthetic components.[13,14] In addition, nonlinear FEA facilitate the simulation of immediate loading conditions with nonlinear frictional contact.[15-18] Previous studies have evaluated the stress accumulation on anteriorly placed implants and peripheral bone by using FEA.[4, 9, 19-22] However, the data on the stress accumulation points when high-performance polymers are used as abutment materials are insufficient.[23] To the authors' knowledge only 1 study, which was in vitro, has ever compared PEEK and PEKK as hybrid implant abutments.[3] In addition, the authors are unaware of a study on the effect of immediate and delayed loading on the stress accumulation on anterior single implants restored with PEEK and PEKK hybrid abutments. Therefore, the present study aimed to evaluate the stress generated on peripheral bone, implant, and prosthetic components while using PEEK and PEKK hybrid abutments under two different loading situations (immediate and delayed) by using nonlinear FEA. The null hypothesis was that there would not be any difference in the stress distribution on peripheral bone, implant, and prosthetic components when an implant is loaded either immediately or delayed by using standard titanium, PEEK, and PEKK hybrid abutments.

MATERIALS AND METHODS

A maxillary bone model was generated by reconstructing a previously obtained computer tomography with a slice thickness of 100 µm. The tomography data was transferred into a 3-dimensional (3D) Slicer software (http://www.slicer.org)[24] in digital imaging and communications in medicine (DICOM) format, and transformed into a 3D model by segmentation process. Subsequently, standard tessellation language (STL) files of the model were exported into a 3D modeling software (Altair Evolve; Altair Engineering) and the bone structure representing maxilla with a cortical bone thickness of 3 mm geometry was modeled. Trabecular bone was generated by referring to the inner surface of the cortical bone, whereas the gingiva was modeled by referring to the outer surface of the cortical bone (gingival thickness was 1.8 mm).

A titanium bone level implant (Ø: 4.1 mm, length:14 mm), a prefabricated titanium abutment, a titanium base abutment, and an abutment screw were designed and modelled after their respective commercial counterparts (SLActive Regular CrossFit; Straumann AG) by using the same 3D modeling software. After that, cement-retained PEEK and PEKK hybrid abutments were designed over the 3D model of the titanium base abutment (Ø: 4.5 mm, height: 3.5 mm, gingival height: 2 mm). The final dimensions of the prefabricated titanium abutment and the hybrid abutments were standardized (height: 6 mm). Following the modelling of the implant and the prosthetic components, a maxillary right central incisor restoration (9 mm in height and 4.8 mm in thickness around the marginal area) in resin nanoceramic (Cerasmart; GC Corporation) was modeled over standard titanium, PEEK hybrid, and PEKK hybrid abutments (Fig 1). A dual-cure resin cement with a layer thickness of 30 µm was generated as previously described.[23] Poisson ratios and elastic moduli of the components, which were based on either manufacturer data or previous researches are given in Table 1.[21, 25-27] Two different clinical situations were considered while placing the 3D model of the implant in the bone structure. The first clinical situation was complete osseointegration and delayed loading, where the bone-implant interface was assumed to be perfect. Immediate loading, which was the second situation, was simulated as nonosseointegrated, and the coefficient of friction between bone-implant interfaces was set to 0.3.[28] In both clinical situations, the fit of abutment to the implant was perfect.

A 4-nodes linear tetrahedral element discretization was performed for all models using a meshing software. (Altair Hypermesh; Altair Engineering). These models, which were assumed isotropic, homogeneous and linearly elastic, were then transferred into a FEA software (Altair Optistruct; Altair Engineering) for the analyses of stress distribution. In the models created, the number of nodes is between 313939 and 472511, and the number of elements is between 1257532 and 1921256.

A total of 6 models were generated according to the combination of implant loading and abutment types: Ti-immediate: standard titanium abutment and immediate loading; Ti-delayed: standard titanium abutment and delayed loading; PEEK-immediate: PEEK hybrid abutment and immediate loading; PEEK-delayed: PEEK hybrid abutment and delayed loading;

PEKK-immediate: PEKK hybrid abutment and immediate loading; PEKK-delayed: PEKK hybrid abutment and delayed loading. Models were subjected to rigid fixation by restricting all degrees of freedom from the nodal points in the upper and distal regions of the cortical and trabecular bone, preventing movement in all x, y, and z axes. The preload generated by the tightening torque was reported as 522 Newton (N)[29] and this stress was included in the analyses as the first load step. To reflect the impact of pre-stress on contact areas (titanium base abutment-implant, titanium base-screw, standard titanium abutment-implant, and standard titanium abutment-screw) between structures with high consistency, a non-linear friction contact with a 0.3 friction coefficient was defined.[30] Two different occlusal forces with a ratio of 1:7[31] were applied to the concave area 3 mm below the incisal edge at the palatal surface of the restoration: a horizontal force (25.5 N) perpendicular to the long axis of the implant and an oblique force (178 N) at 30° to the long axis of the implant (Fig 1).[9]

Von Mises stress analysis was conducted to evaluate the stress distribution in standard titanium abutment, hybrid abutments, abutment screws, and implant. Maximum and minimum principal stress analyses were used to determine stress on cortical and cancellous bone tissues under horizontal and oblique loading.

RESULTS

Figure 2 illustrates the stress values on peripheral bone, implant, and prosthetic components according to loading situation and direction of the applied force. PEEK and PEKK hybrid abutments resulted in similar principal stress values on the implant and von Mises stresses around the neck of the implant, which were higher than those generated by standard titanium abutment. In addition, stress accumulation on peripheral bone was similar in all models. However, standard titanium abutments accumulated more stress than the hybrid abutments.

Stress values on the abutment screw were relatively similar in all models. PEEK generated more stress on the titanium base abutment than PEKK.

The stress distribution on peripheral bone, implant, and prosthetic components of the hybrid abutment models were similar (Figs 3 and 4). In addition, delayed loading led to the accumulation of principal stresses in palatal region of the cortical bone, whereas immediate loading led to the accumulation of principal stresses in buccal region. PEEK and PEKK hybrid abutments had higher maximum principal stresses on cortical bone and minimum principal stresses on trabecular bone when loaded immediately, whereas the minimum principal stresses on cortical bone were higher in delayed loading. Oblique forces mostly generated higher principal stresses than horizontal forces. Loading situation did not affect the maximum principal stress on trabecular bone when the force was applied horizontally, whereas oblique forces generated a slightly higher stress accumulation in delayed loading (Fig 3). Delayed loading generated higher von Mises stress on the implant than immediate loading, while immediate loading resulted in a slightly higher stress accumulation on the neck of the implant. Oblique forces led to higher stress values on the implant and around its neck (Figs 4 and 5). The stress concentrated on the abutment screw was primarily affected by the direction of the force as oblique forces generated considerably higher stress (Fig 6). Oblique forces generated higher stress on both hybrid components (Fig 7) and titanium base abutments (Fig 8) than horizontal forces. Also, delayed loading mostly generated higher stress on hybrid components and titanium base abutments.

Immediate and delayed loading caused different stress accumulations in titanium abutments and oblique forces generated more principal stress on cortical bone than horizontal forces (Fig 3). Immediate loading accumulated higher von Mises stresses on the neck of the implant, whereas delayed loading generated more stress on the standard titanium abutment. However, in both situations oblique forces generated higher stress (Figs 5 and 7). The von

Mises stresses on the abutment screw was higher in delayed loading when the force was applied horizontally, and higher in immediate loading when the force was applied obliquely (Fig 6).

DISCUSSION

Stress accumulation on peripheral bone, implant, and prosthetic components varied among implant abutments and loading situations. Therefore, the null hypothesis was rejected. However, the pattern of stress accumulation on implant and bone structures were similar in all models, regardless of the loading situation or direction of the force. Stresses generated under occlusal loads pass through prosthetic components that include restoration, cement layer, abutment, and prosthetic screw before reaching the bone-implant interface.[23,25] The standardized prosthetic structures in the present study may have contributed to the similar stress distribution, even if abutment materials differed.

A previous study has reported that any von Mises stress value exceeding the yield strength of a titanium implant (550 MPa) might result in failure.[32] None of the implants modeled in the preset study showed a von Mises stress value that was higher than 550 MPa. However, when the PEEK hybrid abutment model wad loaded obliquely in immediate loading situation, the stress accumulated on the titanium base abutment (685.6 MPa) was higher than 550 MPa. This result might be interpreted as PEEK hybrid abutment being more prone to failure (debonding or fracture) when used in immediately loaded situations as the stress was concentrated in the margin of the titanium base abutment. In addition, the principal stress values observed in all models were below the ultimate compressive (167 to 205 MPa) and tensile (100 to 205 MPa) strength limits of the cortical bone,[9,23] and were in the range of the ultimate strength values (1 to 20 MPa) of trabecular bone.[9]

Previous studies have suggested that the elastic modulus of the abutment material might affect the stress transferred to the implant as rigid materials absorb more stress.[12, 33] The von Mises stress values generated in the junction area of hybrid abutments was lower in PEKK hybrid abutment models. This could be related to PEKK's higher elastic modulus compared with PEEK.[3] Even though PEEK has favorable characteristics in terms of stress distribution on implant and peripheral bone structures due to its lower elastic modulus,[23] it might generate more stress on the prosthetic superstructure compared with abutment materials with higher elastic modulus as reported in a previous study by Kaleli et al.[23] Nevertheless, the distribution of stress was similar throughout the PEEK and PEKK hybrid abutment models, except for the abutment-titanium base abutment junction, as only the stiffness of the abutment materials was the difference between models.

Even though an optimal osseointegration is generally assumed in FEA models, there are clinical conditions where the prosthetic restoration is delivered without maximum osseointegration. Therefore, it is crucial to model the imperfect contact between dental implant and bone under intraoral stresses while evaluating immediate loading.[28, 34] Owing to the esthetic requirements of the maxillary anterior region, immediately loaded models were generated along with delayed models in the present study. Stresses accumulated at the implant-abutment junction were higher in immediate loading models, while points of stress were similar in both loading situations regardless of the abutment material or direction of the force.

Optimal loading and appropriate occlusal relations are critical for the health and the sustainability of the peripheral bone structure.[2] In general, immediate loading or oblique forces resulted in more stress in the present study, which complies with previous FEA studies.[23, 34-36] In the present study, a 25.5 N force was applied perpendicularly to the long axis of the implant to imitate protrusive movements,[9, 12] while a 178 N force was applied obliquely to the long axis of the implant with 30° to reflect natural clinical conditions in the anterior region. Nevertheless, in vivo masticatory forces may exceed the oblique and horizontal forces applied in the present study, particularly for those patients with bruxism. Therefore, the results of the present study need further in vivo support.

In the present study, a resin nanoceramic was preferred as the restorative material, due to its shock damping behavior, favorable resilience, and lower modulus of elasticity compared with ceramics.[27] Kaleli et al[23] have concluded that resin-matrix ceramic generated lower stress than translucent zirconia and lithium disilicate glass ceramic in the cervical region of the restoration while restoring PEEK or zirconia hybrid abutments. However, Bergamo et al[27] have reported similar maximum principal stress values on crown, abutment, and cement layer while evaluating 4 different resin-matrix ceramics. Considering those results[23, 27] and the fact that PEEK and PEKK hybrid abutments are scarcely investigated,[3] future studies should investigate the stress distribution when PEEK and PEKK hybrid abutments are restored with different restorative materials.

A limitation of the present study was that PEEK and PEKK hybrid abutments were only compared with a standard titanium abutment. However, zirconia or lithium disilicate hybrid abutments are widely preferred and a comparison among different hybrid abutments might elaborate the knowledge on the clinical performance of PEEK and PEKK. In addition, the present study was limited to a single implant. Even though computational simulations reveal more favorable situation from a biomechanical point of view, they also have disadvantages such as being dependent on models, material properties, load values, and type of application.[36,37] Therefore, controlled randomized clinical trials should be conducted to substantiate the findings of the present study, and broaden the knowledge on the performance of PEEK and PEKK hybrid abutments.

CONCLUSION

According to the results of this study and within its limitations, the following conclusions were drawn. Different abutments affected the stress accumulation as PEEK and PEKK hybrid abutments generated higher stresses on the implant, while standard titanium abutment accumulated more stress than the hybrid abutments. However, stresses generated on the peripheral bone was not affected by the abutment type. Other than minimum principal stress values on trabecular bone, oblique forces generated more principal stress than horizontal forces for all abutment types. The stress accumulated on peripheral bone, implant, and titanium infrastructures in different loading situations was lower than previously reported ultimate and yield strength values; except for PEEK hybrid abutment, which resulted in higher stresses than the yield strength of a titanium implant when oblique forces were applied in immediate loading situation.

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TABLES

Table 1. Properties of the materials used in this study

Material	Elasticity Modulus (E)	Poisson's Ratio (n)
Cortical bone	13.7 GPa [55-57]	0.30 [55-57]
Cancellous bone	1.37 GPa [55-57]	0.30 [55-57]
Titanium implant	110 GPa [53]	0.35 [53]
Titanium base abutment	110 GPa [53]	0.35[53]
PEEK	4.0 GPa*	0.4*
PEKK	5.1 GPa [54]	0.25 [54]
Nanoceramic	10.36 GPa [52]	0.30 [52]

* These values were obtained from the manufacturer's data sheets.

FIGURES

Figure 1. Implant, abutment, crown designs, and the point of force application for the horizontal (black arrows) and oblique loads (red arrows) (A: Standard titanium abutment model, B: Hybrid abutment model)

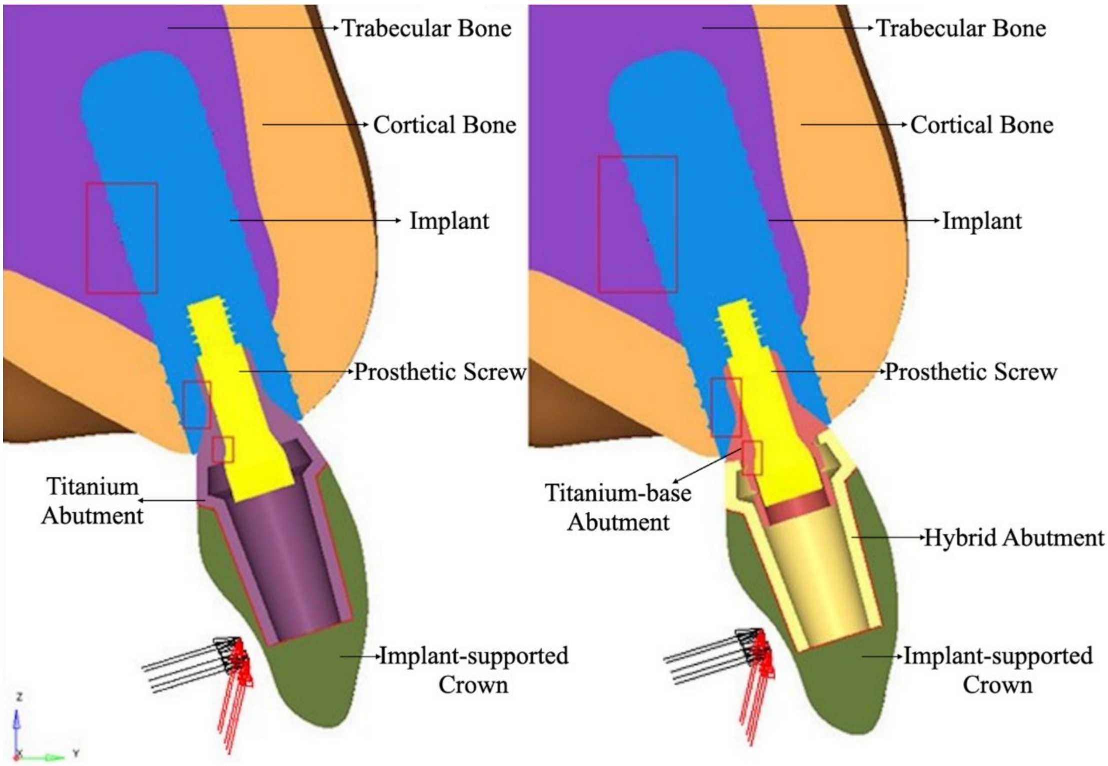

Figure 2. Maximum principal, minimum principal, and von Mises stress values (MPa) in PEEK hybrid abutment, PEKK hybrid abutment, and standard titanium abutment models under horizontal and oblique loading

Figure 3. Maximum principal stresses in cortical (1-4) and trabecular bone (5-8) (A: PEEK hybrid abutments, B: PEKK hybrid abutments, C: Standard titanium abutments, 1/5: Delayed/horizontal loading, 2/6: Delayed/oblique loading, 3/7: Immediate/horizontal loading, 4/8: Immediate/oblique loading)

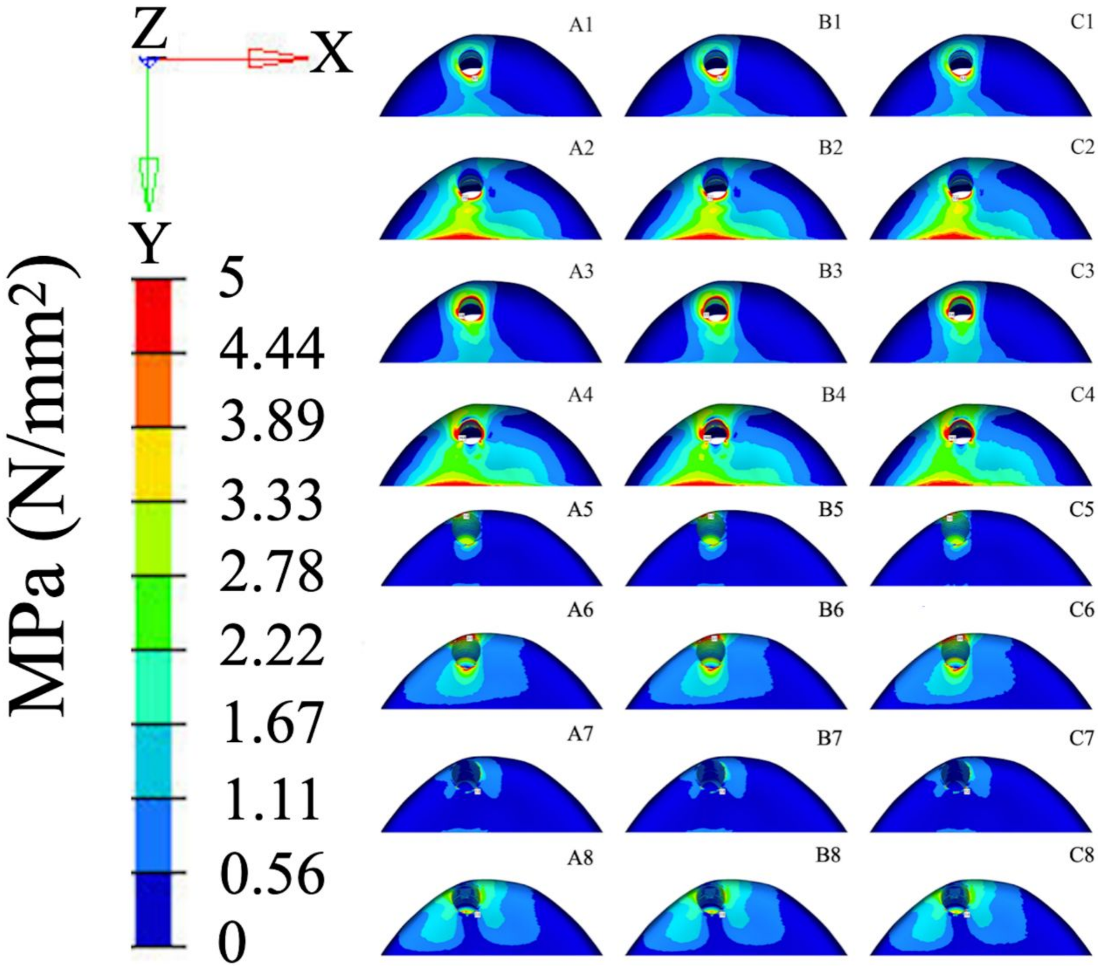

Figure 4. Minimum principal stresses in the cortical (1-4) and trabecular bone (5-8) (A: PEEK hybrid abutments, B: PEKK hybrid abutments, C: Standard titanium abutments, 1/5: Delayed/horizontal loading, 2/6: Delayed/oblique loading, 3/7: Immediate/horizontal loading, 4/8: Immediate/oblique loading)

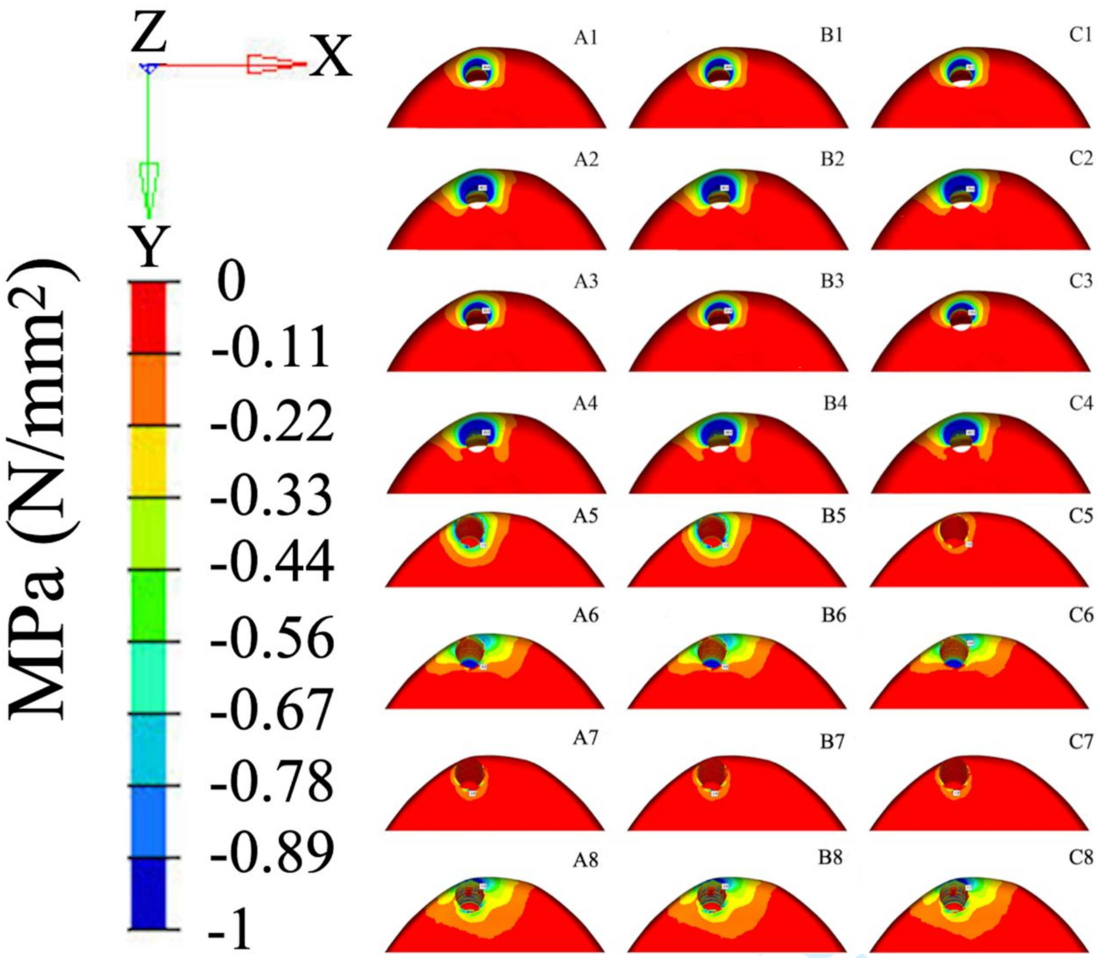

Figure 5. Maximum principal, minimum principal, and von Mises stresses on implants (A: PEEK hybrid abutments, B: PEKK hybrid abutments, C: Standard titanium abutments, 1: Delayed/horizontal loading, 2: Delayed/oblique loading, 3: Immediate/horizontal loading, 4: Immediate/oblique loading)

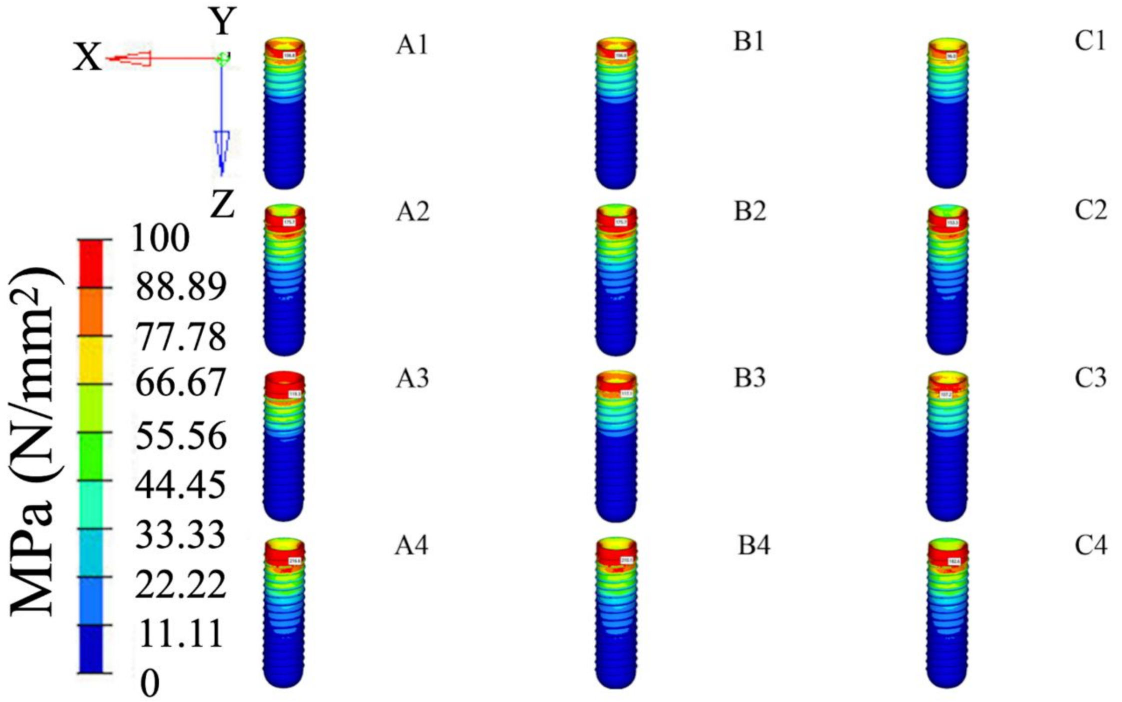

Figure 6. Von Mises stress on abutment screw (A: PEEK hybrid abutments, B: PEKK hybrid abutments, C: Standard titanium abutments, 1: Delayed/horizontal loading, 2: Delayed/oblique loading, 3: Immediate/horizontal loading, 4: Immediate/oblique loading)

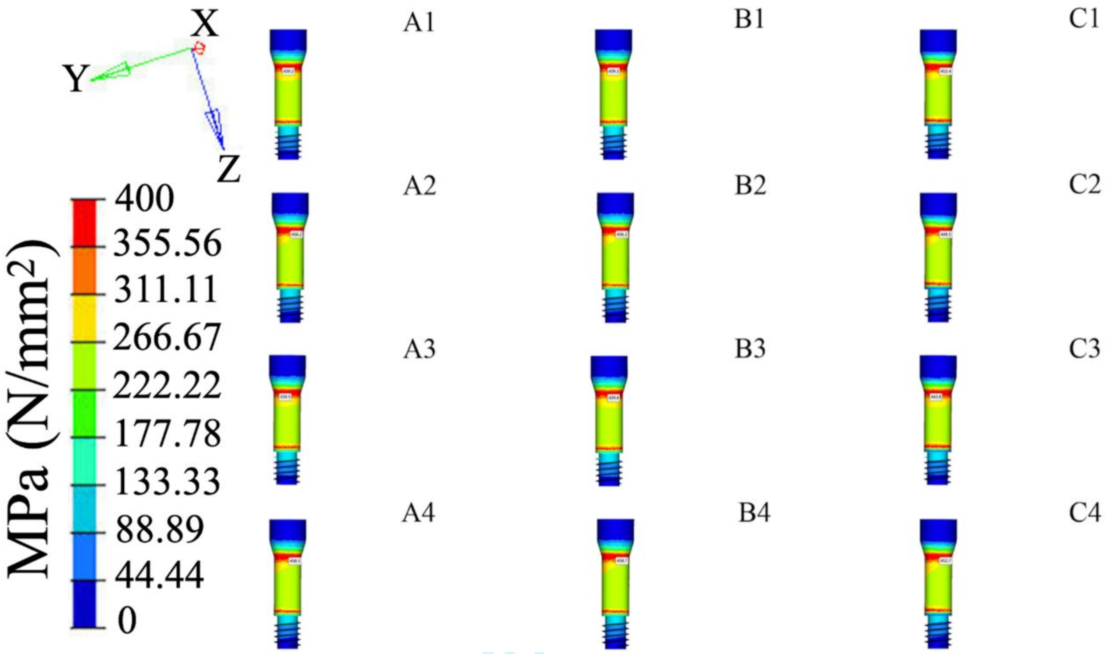

Figure 7. Von Mises stress on abutments (A: PEEK hybrid abutments, B: PEKK hybrid abutments, C: Standard titanium abutments, 1: Delayed/horizontal loading, 2: Delayed/oblique loading, 3: Immediate/horizontal loading, 4: Immediate/oblique loading)

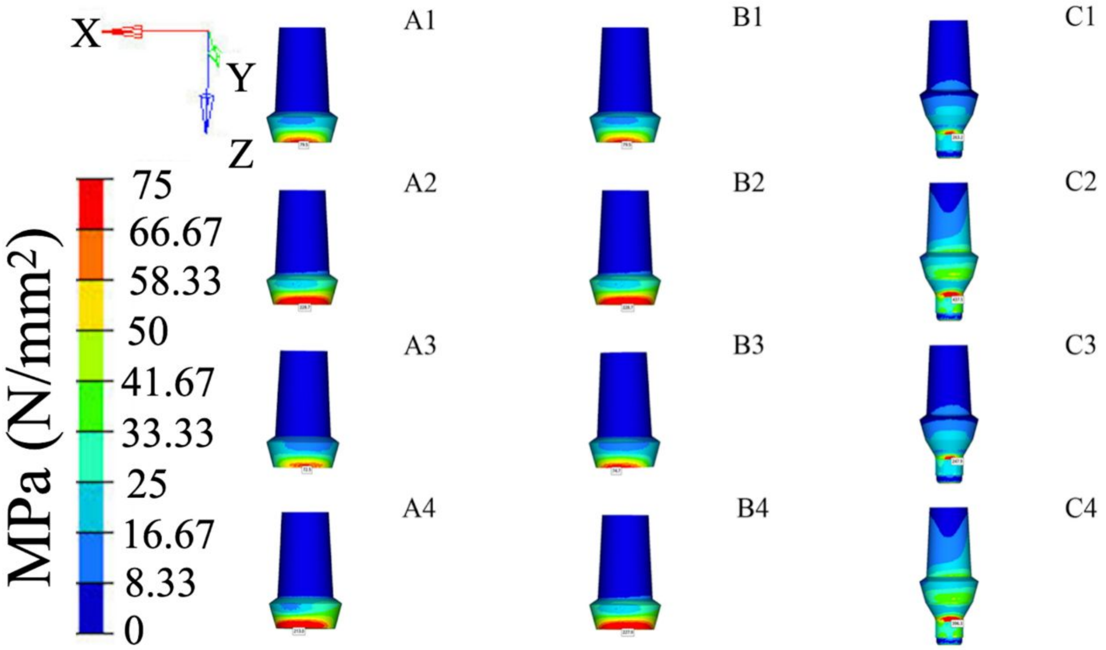

Figure 8. Von Mises stress on titanium base abutment (A: PEEK hybrid abutments, B: PEKK hybrid abutments, 1: Delayed/horizontal loading, 2: Delayed/oblique loading, 3: Immediate/horizontal loading, 4: Immediate/oblique loading)