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RESEARCH ARTICLE

COMPARISON OF MECHANICAL PROPERTIES OF THE IMPLANT MATERIALS- TITANIUM, ZIRCONIUM AND PEEK USING THREE DIMENSIONAL FINITE ELEMENT ANALYSIS

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Abstract

Background And Objective: Dental implants have been universally accepted as the best option for prosthetic rehabilitation of missing teeth.A material of choice for manufacturing dental implants was for long time commercially pure titanium due to its excellent bio compatibility and mechanical properties. Zirconia seems to be a suitable alternative dental implant material because of its tooth like color and biocompatibility. The most promising novel alternative to titanium is polyetheretherketone (PEEK) which is a partially crystalline poly aromatic linear thermoplastic substance. The objective of this study is to study and compare the mechanical properties of titanium, zirconium and PEEK implant materials using three dimensional finite element analysis.

Methodology: A randomly chosen computerized tomography was used to obtain the digital model in the initial phase of the work. Only the part portion corresponding to tooth number 35 will be extracted from this model. Screwed cylindrical implants of length 12 mm and diameter 4mm will be modeled and simulated to be placed in the section of the bone. The different models used were model A - Titanium, model B – Zirconium, and model C - PEEK implant models. All models were identical, except for the properties of the used materials and all were exported to the Ansys Workbench V10 finite elements simulation software. Vertical and oblique (45 degree) loads in relation to the long axis of the tooth with 100 N in magnitude were applied. Stress analysis performed by comparing the Von Mises stress components. Fatigue strength and mode of failure were also assessed for the three implant materials.

Results: Maximum stress in the peri-implant bone when titanium implant was placed in 35 region was 281.40 Mpa under axial load of 100N. Maximum stress when zirconia implant was placed is 277.99 MPa and when peek implant was placed which amounts for 286.78Mpa. Titanium sustains more life cycle (832840.00) compared to Zirconium (743070.00) and PEEK has much less life cycle (302460.00). Factor of safety is rated on a scale of 0 -15 and results

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were Titanium (12.42) and Zirconium (11.16) had almost similar values. Peek (6.15) had low safety factor compared to Titanium and Zirconia.
Conclusion: Titanium was superior to other two groups in all the properties considered. These results prove why Titanium is still considered to be the gold standard material of choice for dental implant fabrication.

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Introduction:-

Successful replacement of lost natural teeth is one of the challenging tasks which has been besetting the mankind for several decades. Among the diverse options available, dental implants have been universally accepted as the best treatment modality to replace partially and completely edentulous patients owing to its biocompatibility, excellent esthetics, resistance to fracture and osseo integration properties(1).

Broad array of materials have been in use and new biomaterials keep emerging every day for the manufacture of dental implants with ideal physical and mechanical properties. Most widely used among those are Titanium and its alloys, vitallium, vitreous carbon and ceramics with endosteal and subperiosteal designs(2).

Biocompatibility is of paramount importance during selection of suitable implant material. Commercially pure titanium and its alloys are still considered the “gold standard” material of endosseous implants for its excellent biocompatibility, corrosion resistance and high strength. But titanium implants do have some drawbacks such as bluish grey appearance of the implant itself and the esthetic compromise in areas of thin overlying mucosa. The elastic modulus and strength of titanium and its alloys are much higher than bone which can result in impaired load force transmission at the implant tissue interface contributing to stress shielding and peri implant bone resorption(3).

The introduction of Yttria partially stabilized Tetragonal Zirconia polycrystals is one of the hallmark evolution of implant biomaterials (Y-TZP) (4).Zirconia or ceramic steel possess excellent biomechanical properties such as flexural strength and fracture toughness making it the most promising material to be used as bio-medical implants. The color of Zirconia is one of the advantageous factor over metal alloys which has the limitation of causing grey discoloration to the surrounding soft tissues. One promising feature about zirconia implants is the low bacterial adhesion against the implant surface. A significant reduction in pathogenic bacteria and low plaque adsorption and retention was observed which led to much lower bone resorption rates(5).

The promising novel alternative to titanium to overcome the shortcoming of relative stiffness difference between bone and implant is polyetheretherketone (PEEK) which is a partially crystalline poly aromatic linear thermoplastic substance. Although pure PEEK exhibit elastic modulus that varies from 3 to 4 GPa, this value can be modified to achieve a tensile strength of 90-100 Mpa and elastic modulus as near to cortical bone (18 GPa) with the addition of composites, such as carbon fiber (CFR-PEEK). This property minimizes the stress by distributing it in more physiologic manner supporting bone formation around bone and reduces osteolysis(6).

Stress and strain developed around the crestal bone are crucial factors affecting successful osseointegration. Highest concentration of stress is observed in the crestal regions(7). It is important to study the stress and strain distributions around different types of dental implants. In addition to stress and strain, other mechanical properties like fatigue strength and failure mode should be assessed to select an appropriate implant biomaterial for a particular clinical situation. Several methods including photoelastic studies, strain gauge and finite element analysis have been used to investigate the stress in the peri-implant region and in the components of the implant supported restorations.

There is still lack of proper evidence regarding the mechanical properties of dental implant biomaterials. Hence the purpose of this study is to evaluate mechanical properties like stress and strain distribution around peri-implant bone in premolar region and fatigue strength and failure mode of implants of different materials like titanium, zirconia and PEEK.

Materials And Methods:-

Finite element analysis is a widely used numerical method to understand and quantify any physical phenomenon for instance analysis of stress and deformation in structures of any given geometry. It is widely accepted as a non-invasive and excellent tool for studying the biomechanics and the influence of mechanical forces on the biological system.

For this study a randomly chosen computerized tomography was used to obtain the digital model in the initial phase of the work. The obtained CT scan was then imported to an image processing and digital reconstruction program to obtain the 3D mandibular model. The mandibular bone was modeled with cortical bone thickness of 1.5mm enclosing a trabecular bone core. Properties corresponding to D2 bone were used (D2 bone 850- 1250 hounse field units). Only the part portion corresponding to tooth number 35 will be extracted from this model. Bone block was modeled to be 12mm length and buccolingually 8mm wide to incorporate the implant dimension in it.

Nonliving structures including implants, abutments and final prosthetic restorations substantially influence the stress and strain values similar to living structures. Each of these component were scanned separately and assembled together to convert into 3D solid. Solid cylindrical implants of 12mm length and 4mm in diameter is modeled and simulated to be placed in the region of left mandibular premolar as depicted in figure 1-4.

The 3D geometry was exported to FEA preprocessing software (ANSYS Inc., Canonsburg, PA). A mesh of 326522 nodes and 189836 elements was generated for the FEA models. All materials were assumed to be isotropic, homogeneous, and linearly elastic. Young moduli and Poisson ratios of the materials used in the present study are shown in Table 1 and 2. The bone implant interface was considered completely fixed, in order to simulate an osseointegrated situation, and there were no craterlike defects around the implant neck, or gaps in the implant‑ abutment and abutment cylinder connections. Among the implants, bone and the prosthetic structure a perfect fit situation was assumed.

Load

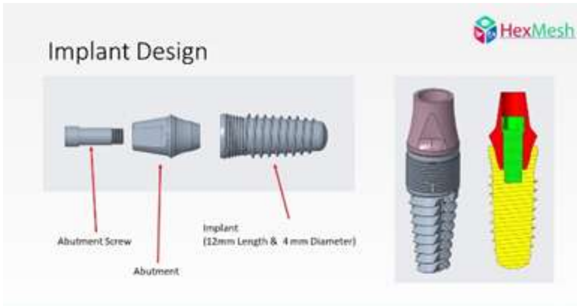
Both axial and oblique loads at 45 degree were applied. Since the average masticatory force ranges from 100N – 300N, load value of 100N was used in this study. Mathematical solutions obtained in results were converted into visual results characterized by degrees of color, ranging between red and blue, with red presenting the highest stress values.

Table 1:- Material Properties.

s no	properties	units	titanium	zirconium
1	Density	g/cm3	4.43	6.53
2	Modulus of elasticity	Gpa	113.8	94.5
3.	Poissons ratio		0.34	0.34
4	Yield strength	Mpa	880	230
5	Tensile strength	Mpa	950	330

Table 2:-Properties Of Living Structures.

S no	Properties	Units	Cortical bone	Cancellous bone
1.	Density	g/cm3	1.9	0.53
2	Modulus of elasticity	Gpa	13.7	6
3	Poissons ratio		0.3	0.35
4	Yield strength	Mpa	40	42
5	Tensile strength	Mpa	151	51



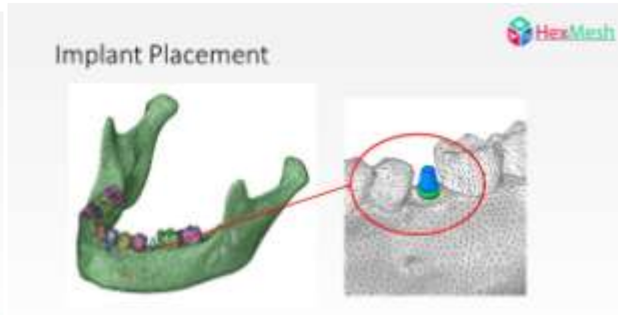


Figure 1: Implant Design

Figure 2: Mesh model of implant placement

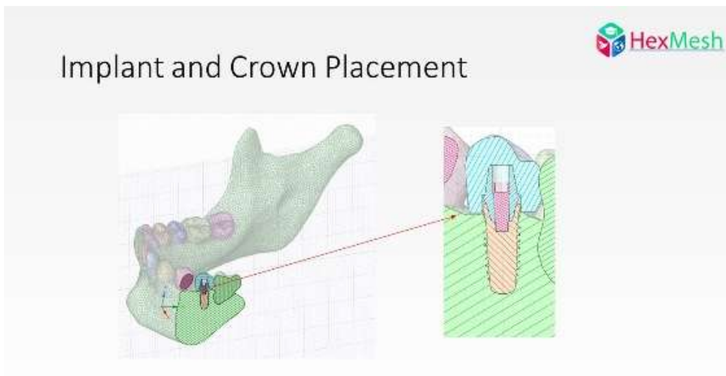


Figure 3: Cross sectional view of implant and crown placement

FIGURE 4: Final view of prosthesis in 35 region

Results:-

Stress distribution in the FE models comes in numerical values and in color coding. Maximum values of von mises are denoted by red color and minimum value by blue color. The values in between maximum and minimum are represented by bluish green, greenish yellow and yellowish red in the order of minimum to maximum.

Maximum peak stress under different structures are listed under table 3. Maximum stress in the peri-implant bone when titanium implant was placed in 35 region was 281.40 Mpa under axial load and 294 MPa under oblique loading. Maximum stress when zirconia implant was placed is 277.99 MPa and 289 Mpa under axial and oblique loads respectively, slightly less compared to titanium. However, stress was comparatively higher when peek implant was placed which amounts for 286.78Mpa and 301.77MPa, but there was no significant difference between the three groups.

Failure mode and fatigue strength of the implants were assessed based on the number of life cycles it survives, stress that the implant material is subjected to and factor of safety which is based on ratio of strength of the material and maximum stress it sustains ,values depicted in table 4. Under axial loading and lateral loads, Titanium has sustains more life cycles compared to Zirconium and PEEK has much less life cycle.

Factor of safety is the ratio of maximum strength of the material and stress it can sustain until it fractures. Factor of safety is rated on a scale of 0 -15. Under axial loading Titanium (12.42) and Zirconium (11.16) had almost similar values. Peek (6.15) had low safety factor compared to Titanium and Zirconia.

Under oblique loading also, Titanium (8.15) and Zirconia (7.40) had almost similar values but the values decreased compared to the safety factor values under axial loading. PEEK had very less safety factor of only (5.17).

Failure mode and fatigue results based on stress was also analyzed and compared both under axial and oblique loading. Based on stress, Titanium performed better than PEEK and Zirconium by producing stress of 795.83 MPa under axial loading. Zirconia produced 809.88 MPa and PEEK had the maximum values (890.24 Mpa) which is very high compared to other two groups.

Under oblique loading also PEEK produced higher stress values than the other groups (1334.04 MPa). However, Titanium showed 1246.77 MPa under oblique loading which is higher than under axial loading. Zirconium showed 1280.20 Mpa which is close to stress showed by Titanium.

Table 03:- Comparison Of Maximum Stress Values In Different Structures When Different Implant Materials Were Used Under 0,45 Degree And 90 Degree Loading.

S.No	Result Value	Titanium			Peek			Zirconium			Unit
		0 Deg	45 Deg	90 Deg	0 Deg	45 Deg	90 Deg	0 Deg	45 Deg	90 Deg	
1	Crown Stress Maximum	19.14	30.99	65.13	19.13	31.08	65.33	19.16	30.97	65.01	MPa
2	Bone Stress Maximum	281.40	294.38	286.39	286.78	301.77	295.55	277.99	289.92	281.14	MPa
3	Abutment Stress Maximum	61.55	149.57	329.08	63.13	158.13	354.54	60.73	145.41	315.44	MPa
4	Abutment Screw Stress Maximum	19.65	46.26	105.29	19.62	45.51	93.18	19.90	54.96	117.72	MPa
5	Implant Stress Maximum	795.83	1246.77	1692.41	890.24	1334.04	1792.42	809.88	1280.20	1749.44	MPa

Table 4:- Failure Mode And Fatigue Strength Of Implants Under Axial And Oblique Loads Based On Life Cycle, Factor Of Safety And Stress.

Test	Force	Implant Result	Life Cycle	FOS (0-15)	Stress (Mpa)
Implant	0 Deg	Titanium - 100N	832840.00	12.42	795.83
		PEEK - 100N - 0DEG	302460.00	6.15	890.24
		Zirconium - 100N - 0DEG	743070.00	11.16	809.88
	45 Deg	Titanium - 100N - 45DEG	620494.00	8.15	1246.77
		PEEK - 100N - 45DEG	288605.40	5.17	1334.04
		Zirconium - 100N - 45DEG	588953.60	7.40	1280.20
	90 Deg	Titanium - 100N - 90DEG	301525.00	6.45	1692.41
		PEEK - 100N - 90DEG	60473.40	3.16	1792.42
		Zirconium - 100N - 90DEG	160283.50	5.15	1749.44

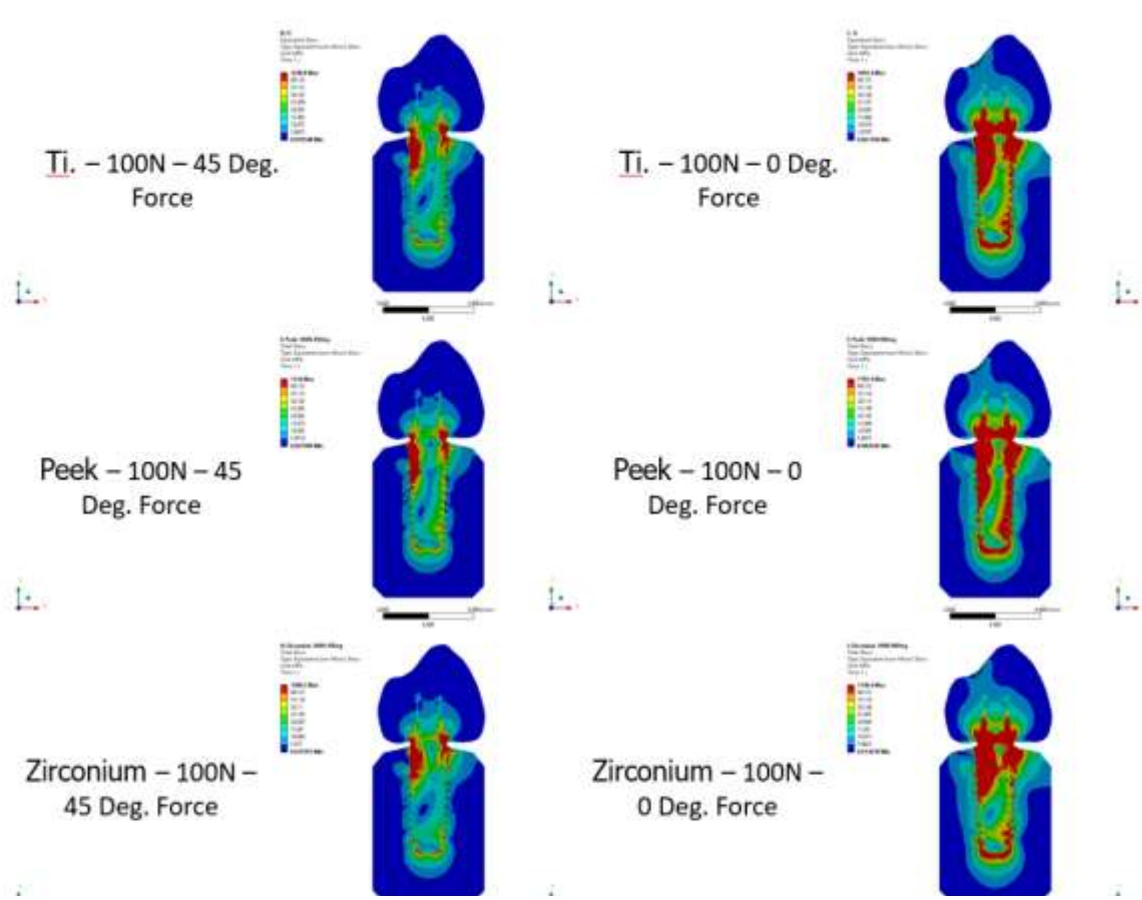


Figure 5:- Comparison of Von mises stress, strain and deformation of Titanium , Zirconium and PEEK implants under axial and oblique loading.

Discussion:-

Dental implants have become the preferred treatment option both for totally and partially edentulous patients because of the comparatively high success rate compared to fixed partial denture and removable partial denture. . There are several variables influencing successful osseointegration and its maintenance which can be divided into surgical factors, host related factors, implant or occlusion related factors. Mechanical stress transmitted to the surrounding bone has to be within limits such that it positively influences the bone by remodeling and successful maintenance of implant osseointegration(2).

Titanium was considered in the study because titanium still continues to be preferred material of choice for the fabrication of dental implants for rehabilitation of partially and fully edentulous patients(8). Zirconia implants were considered in the study as zirconia dental implants has proved to be viable alternative to titanium and esthetically zirconia performed superior to titanium especially in anterior esthetic zones(9). PEEK implants were considered in this study because various studies proved PEEK to be a better alternative to titanium implants because of its modulus of elasticity close to human jawbone(6).

Although implants are widely used many factors regarding its biomechanical aspects remain poorly understood. In the maintenance of bone -implant interface, biomechanical factors play an important role(10). Unlike the natural tooth where periodontal ligament distributes stress evenly, Implants lack the stress releasing phenomenon(11).

Hence, the aim of the three-dimensional finite element analysis was to compare the mechanical properties including stress and strain, fatigue strength and failure mode of three different implant materials placed in partially edentulous mandible in 35 region.

The results obtained after loading showed that all three implant materials had almost similar stress values in the peri-implant bone with minor differences. When the implant is loaded both axially and obliquely, PEEK transmitted slightly higher stress compared to zirconium and Titanium. This is similar to the study conducted by Andreas Schwitalla where the CRF-PEEK implants presented higher load concentration in the cervical area and cortical bone than the titanium implants. Titanium implants presented equivalent stress peaks compared to PEEK implant(12). In this study, Zirconia performed slightly better in stress distribution to the peri-implant bone among the three materials similar to a study by Camilo Andres Villabona Lopez to compare the principal peak stresses in the peri-implant bone around titanium and zirconia implants using the finite element method. Zirconia implants decrease the stress peaks at the peri-implant bone area around the implant platform when compared with titanium implants(13).

With respect to stress values within the implant, Peek implant was subjected to more stress compared to the titanium and zirconium implants which is because of the very low modulus of elasticity due to the absence of lateral contact with other structures, transferring the stresses to the implant and peri-implant bone tissue. This result is comparable to the study conducted by Jao Rodrigo et al who evaluated the stress distribution in CRF-PEEK dental implants and titanium implants by three dimensional finite element method in which CRF-PEEK presented higher stress concentration in the implant neck due to decreased stiffness and higher deformation in relation to titanium(14).

In this study fatigue strength and failure mode of the three implant materials were assessed based on number of life cycles the material survives when it is loaded, the stress the material is subjected to and factor of safety which is the ratio of maximum strength of the material to stress it can withstand before fracture. According to the obtained results Titanium was much superior to PEEK and zirconium. PEEK exhibited the least number of life cycles when loaded. However, Zirconium performed better to PEEK but slightly lesser than Titanium with respect to life cycle. This is in accordance with the study conducted by Woo TaeK Lee where he compared fatigue limits of PEEK with Titanium. Contrary to finite element analysis, fatigue tests were done under dry conditions at room temperature in this study. During compressive strength testing titanium rod bent until 4mm without fracture whereas the PEEK specimens fractured. However, this study concluded that GRF-PEEK implants can withstand a static and cyclic load that is comparable to the maximum bite force in anterior dentitions(15).

Factor of safety based on the maximum strength of the material and maximum stress it can withstand was assessed and compared for the three implant materials. It was rated on a scale of 0-15. As its inversely proportional to the stress the implant is subjected to and comparatively not so strong material, PEEK implants had much lower safety factor compared to titanium and Zirconium which had almost similar values.

All the assessed parameters clearly indicate why titanium continues to be the gold standard material of choice for dental implant treatment. Zirconia also exhibits various features that are close to titanium, especially zirconium performs better than titanium with respect to stress distribution to the peri-implant bone due to its stiffness. Hence zirconium can be considered as a suitable alternative to titanium implants especially in the esthetic regions.

The limitations of the study were that it is an in vitro software based study where 3D model of the mandible was designed from the CT scan of any patient with missing 35. Further investigations including more complex set up with more realistic material properties like anisotropy are needed to achieve better understanding of load distribution and failure mode and fatigue strength of dental implants.

Conclusion:-

From the finite element analysis method to assess the stress distribution in the peri-implant bone using Titanium, Zirconium and PEEK dental implants, the following conclusions can be made

i. There was a tendency of higher stress/strain in bone tissue caused by materials presenting lower elastic modulus (PEEK), they also presented higher stress concentration in the implant.

ii. Zirconia implants led to lower stress/strains in bone tissue owing to its higher elastic modulus. Zirconia implants have stress distribution closely similar to Titanium implants and may be a viable alternative to titanium implants.

There is a lack of literature focusing on the fatigue limits and failure mode of implant materials under various conditions of loading. Conclusions drawn from this study with regard to fatigue limits and failure mode were

i. Titanium sustains more life cycles compared to zirconium and PEEK under loading.

ii.PEEK showed much lower safety factor compared to Titanium and Zirconium

iii. PEEK implants were subjected to more stress than Titanium and Zirconium implants. Titanium was superior to other two groups in all the properties considered. These results prove why Titanium is still considered to be the gold standard material of choice for dental implant fabrication.

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