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BIOMECHANICAL STRESS ANALYSIS OF OVERDENTURES SUPPORTED AND RETAINED BY PEEK IMPLANTS AND ATTACHMENTS USING DIFFERENT DESIGNS : A 3D FINITE ELEMENT ANALYSIS STUDY

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ABSTRACT

Background: Analysis of stresses induced by using poly ether ether ketone (PEEK) implants and prosthetic attachments for implant supported mandibular complete overdenture. **Methods:** 3D finite element model was made for lower complete overdenture, supported by implants (4 mm in diameter, 12 mm in length) and retained by ball attachments. Linear static stress analysis was carried out by ANSYS 2020. Three model cases were created. Model 1 supported by two Ti implants in canine region, Model 2 supported by three PEEK implants (2 in canine region, 1 in midline), Model 3 supported by 4 PEEK implants bilaterally in canine and premolar region. Same material either titanium alloy or PEEK was used in modelling all prosthetic components in each case model. Application of force (120 N) bilaterally was carried out 3 times for each model case (vertical, oblique and lateral). **Results:** Model 3 showed the highest maximum and minimum principal stresses, in peri-implant cortical bone and exceeded its tensile and compressive yield strength after lateral loading. In model 2 Cortical bone maximum and minimum principal stresses did not exceed its yield strength, in the three loading scenarios. However, cortical bone tensile stresses labial to midline implant in model 2 showed low safety factor. **Conclusions:** Model 2 design could be promising biomechanically, if used in normal density bone, but with caution against the critical high tensile stresses at the cortical bone labial to midline implant. While model 3 design could result in excessive high stresses leading to yielding and resorption of cortical bone.

KEYWORDS: PEEK, Finite element analysis, mandibular overdenture, peri-implant bone, cortical bone

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INTRODUCTION

Edentulous patients often experience retention issues with their mandibular denture. The use of implants provides a secure foundation for the denture, significantly reducing concerns about non-retentive dentures. The quantity of accessible bone and the number of implants inserted are crucial factors that determine the potential treatment options. In some cases, only two implants may be used in the mandible to support an overdenture [1].

The inter-foraminal region of the mandible, is often used for placing implants for mandibular overdenture. This region is divided into five equal columns of bone, labeled as **A, B, C, D**, and Considering **C** is in the midline, **B** and **D** are in the canine area, and **A** and **E** are in the first premolar area [1].

Although the number of implants required to ensure a good prognosis with mandibular implant overdenture treatment remains debatable, it was pointed out that the value of fewer implants as a cost-saving approach has an advantage for many patients. However, the use of more than two implants is recommended in special cases to produce greater overdenture stability and preserving the supporting peri-implant bone [2].

According to Wolff's law, when a dental implant is inserted in the jaw bone, it acts as a new "root" that stimulates the bone, much like a natural tooth root. This stimulation encourages the bone to maintain its contour and density, which is crucial for the stability of the implant. However, it's important to note that this remodeling process requires time and appropriate loading conditions. Overloading or improper loading of the implant can lead to bone loss and implant failure[3].

Titanium (Ti) is considered the gold standard for dental implants, due to its rigidity and longevity. However, concerns regarding stress shielding effect and its ability to distribute mastication forces in a pattern that would not affect jaw bone are still questionable. Titanium alloy having an elastic modulus of about (110 GPa) which is different to that of bone (14 GPa), this would affect the distribution of load over the prosthetic appliance, accordingly new researches for introduction of new materials that might have a better pattern of stress transfer to the surroundings were carried out [4 5]. Also, recently concerns aroused about toxicity and biocompatibility of titanium implants [6].

Polymeric materials which are categorized as ultra-high performance—have attracted interest. The polyaryletherketones (PAEKs) family of ultra-high performance thermoplastic polymers includes polyetherketoneketone (PEKK) and polyetheretherketone (PEEK). These semi-crystalline polymers are characteristic for their superior mechanical properties, which had drawn the attention of researchers and clinicians to investigate their use in multiple dental prosthetic designs, implants, and related products as a substitute for titanium [7].

Currently, PEEK research studies usually lack large-scale animal testing and randomized controlled clinical trials. Combining with the complex specific dynamic environment of the human body, future research should focus on animal experiments and clinical research with cyclic loading and long observation time and combine multidisciplinary efforts to achieve a broader application of PEEK [8].

FEA is a method used to predict stress and strain at any point in any given geometric shape via theoretical mathematical models. It is considered a valuable tool to predict, adjust, and prevent future failures in standardized circumstances of research studies [9 10].

In the current study, a biomechanical comparison by finite element analysis (FEA) was made between a standard overdenture supported by two mandibular titanium implants, and two designs of mandibular PEEK implant supported overdentures, one was supported by 3 PEEK implants, and the other was supported by 4 PEEK implants.

METHODS

Finite element modeling:

Finite element model, based on the work of Geng et al.[11], was fabricated specially for this study, to simulate the clinical situation where an edentulous mandible was restored with implant supported overdenture.

The overdenture geometry was modelled by using a laser scanner (Geomagic Capture, 3D Systems, Cary, NC, USA). The scanner exported a data file containing a cloud of points coordinates (STL file). An intermediate, software was required (3-Matic version 7.01 - Materialise NV, Leuven, Belgium) to trim and create outer surface by the acquired points. Then, the solid (closed) overdenture's geometry was exported as IGES file format. Then afterwards, this file was imported to an engineering CAD/CAM software "Solidworks" Version 2014 (Dassault Systèmes Inc., 13090 Aix-en-Provence, France), to remove any errors might appear during transforming the cloud of points into solid geometry. Finally, exporting the solid part (overdenture) as a STEP file format [12].

"Sky classic" regular platform dental implant (bredent medical GmbH & Co. KG · Weissenhorner Str. 2 · 89250 Senden · Germany) with a nominal diameter of 4.0 mm, a length of 12 mm (REF kSKY4012) [13], with the shape of internal Torx 2.1 mm was modeled on engineering CAD/CAM software "SolidWorks" Version 2014 (Dassault Systèmes Inc., 13090 Aix-en-Provence, France), by the drawing of an implant model offered by the manufacturer.

Also, other prosthetic elements related to the same implant system (SKY implant system) like ball attachment (REF SKY-KA02), gingival former, rubber O-ring and the metal matrix (REF SKY-OR50) were also modeled according to the same manufacturer's catalogue data [13]. These components were exported as STEP files, to be assembled in the finite element package as presented in Figure 1.

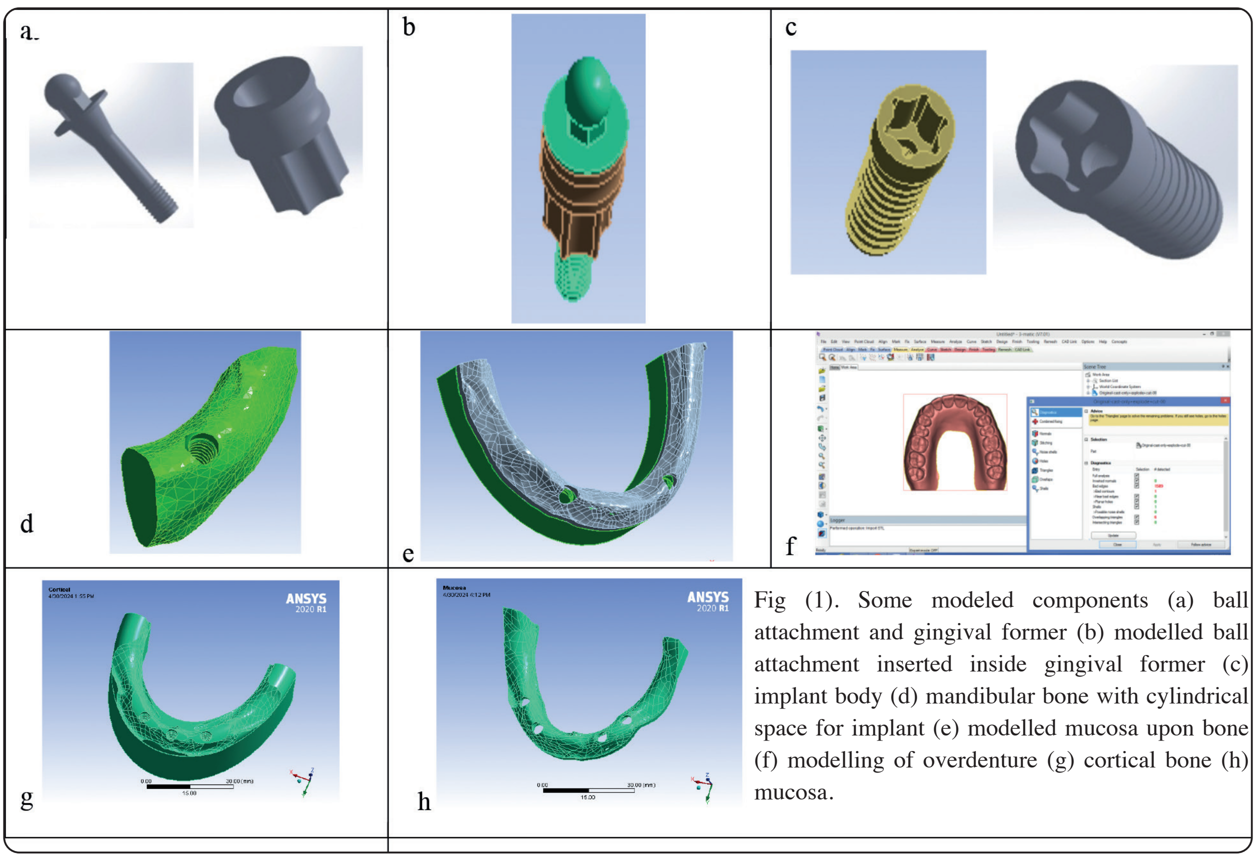

Fig (1). Some modeled components (a) ball attachment and gingival former (b) modelled ball attachment inserted inside gingival former (c) implant body (d) mandibular bone with cylindrical space for implant (e) modelled mucosa upon bone (f) modelling of overdenture (g) cortical bone (h) mucosa.

A thickness of two millimeter for mucosa and cortical bone layers were created by extruding the lower surface of the laser scanned overdenture. Two U shaped extruded areas were created to make volume for cortical and cancellous bone and glued to the other bone layer. Full bond was assumed between 2 types of bone and between cortical bone and mucosa. It was assumed that complete osseointegration was presented between implant and bone. The frictional contact conditions between rubber O-ring from one side and ball attachment / matrix from the other side took the value of 0.3 frictional coefficient. Also, frictional contact between fitting surface of overdenture and mucosa had the value of 0.3 frictional coefficient.

Set of Boolean operations between the modeled components were made to create spaces for internal components, before obtaining the complete model assembled. Meshing of these components was done by 3D brick solid element "Solid-185" [14], which had three degrees of freedom (translations in main axes directions). The resulted numbers of nodes and elements are listed in Table 1.

MATERIALS

Three finite element models, based on Geng et al.[11], were created and utilized. To simulate the clinical situation where an edentulous mandible was restored with an overdenture retained by ball attachments and supported by implants, using three different protocols, as following:

- Model 1: Two titanium alloy implants were placed in the canine region.
- Model 2: Three polymeric PEEK implants were used, two implants in the canine region and the third one in the midline region.
- Model 3: Utilized four polymeric PEEK implants, two in canine region and another two in the premolar regions to support the overdenture.

In each case monolithic principle was used for modeling of prosthetic components, as the same material was used for modeling the implant body, gingival former, ball attachment and the housing matrix in each case, the two materials were: Titanium alloy (type V) and PEEK. On other hand, the same

TABLE (1) Number of nodes and elements for each modeled component.

	Model 1: Two Ti implants		Model 2: Three PEEK implants		Model 3: Four PEEK implants	
Component	Number of Nodes	Number of Elements	Number of Nodes	Number of Elements	Number of Nodes	Number of Elements
Overdenture	425,229	266,944	430060	269830	435,275	273,105
Mucosa (2mm)	42,453	23,614	43281	24100	44,968	25,057
Cap	134,596	40,354	201537	120759	268,716	161,012
Fluoro-rubber ring (Cap)	48,536	28,320	73029	42645	97,372	56,860
Implant	45,580	26,632	558774	345279	745,032	460,372
Collar (2mm)	157,772	97,382	236658	146073	315,544	194,764
Ball attachment	372,394	230,128	68262	39876	91,016	53,168
Cortical bone (2mm)	115,759	71,389	133406	83135	150,042	94,153
Spongy bone	28,578	17,456	34766	21568	40,490	25,387

materials were used for modelling overdenture and O-ring in all cases, which were acrylic resin and plastic-Fluro-rubber respectively.

All materials were assumed to be isotropic, homogenous, and linearly elastic and their properties are listed in Table 2. These materials were assigned to the models' components and meshing convergence test was performed.

TABLE (2) Material properties

Material	Young's modules [MPa]	Poisson's ratio	References
Acrylic resin	2,830	0.45	[15]
Mucosa	1	0.37	[16]
Fluro Rubber O-ring	4	0.37	[16]
Titanium alloy	110,000	0.35	[17]
PEEK	3,700	0.40	[15]
Cortical bone	14,700	0.30	[15], [18]
Cancellous (spongy) bone	1,470	0.30	[15]

Constraints and loading conditions:

The lower surface of the mandibular cortical bone as set to be fixed in place as boundary condition. Three load cases located on central fossa of first molars (on both sides simultaneously) were tested as; (a) 120 N [19] vertical (compressive), (b) 120 N Oblique at 45˚ degree buccolingual., and (c) 120 N lateral (horizontal) buccolingual.

Convergence test and analysis:

The meshing convergence test was performed by applying test load on different mesh densities, in order to ensure results accuracy for the discrete model.

Upon the understanding of the physics of the studied system and sufficient accuracy level to be achieved, initial mesh (coarse one) was examined and its resultant maximum Von Mises stress on implants body was recorded. By running simulations with finer set of meshes and comparing the results, and when no significant difference from one run to another (less than 3%) was recorded, that indicated this mesh was fine enough and the stress results were accurate.

Linear static analysis was performed on Workstation HP Z820 (Dual Intel Xeon E5-2670 v2 processors, 2.5 GHz, 64.0 GB RAM), using commercial multipurpose finite element software package (ANSYS version 2020 R1), that results of these models were verified against similar studies [20].

RESULTS

A Total of nine runs were performed during this study. As for each model case (2 titanium alloy implants, 3 PEEK implants and 4 PEEK implants) there were three loading scenarios (vertical, oblique and lateral).

Maximum von Mises stresses:

Maximum von Mises stresses values were extracted for implant body in each case model in the nine runs. Max von Mises stresses values together with images of stress distribution from ANSYS 2020 in the nine runs, were used to evaluate stress distribution in the ductile implant body [21], and in peri-implant cortical and spongy bone [22] (Figure 2-4).

Maximum and Minimum principal stresses for cortical and spongy bone:

Due to the brittle and ductile nature of cortical and spongy bone [23,24,25], their Maximum and minimum principal stresses values were extracted in the three case models in the three loading scenarios, for the sake of failure theory analysis (Figures 5 and 6). Extracted values of maximum and minimum principal stresses (MaxPS and MinPS) for peri-implant cortical bone are listed in table 3, Extracted values of maximum and minimum principal stresses (MaxPS and MinPS) for peri-implant spongy bone are listed in table 4.

TABE (3) Maximum and Minimum principal stress values for cortical bone in the three model cases of Ti, 3 PEEK and 4 PEEK models.

	Units	MPa	MPa
	Cortical bone	Maximum Principal	Minimum Principal
R1	Model 1 Vertical loading	27.90	55.11
R2	Model 1 oblique loading	26.69	35.91
R3	Model 1 lateral loading	35.91	54.47
R4	Model 2 Vertical loading	90.88	54.07
R5	Model 2 oblique loading	56.93	53.9
R6	Model 2 lateral loading	82.21	57.72
R7	Model 3 Vertical loading	44.30	121.45
R8	Model 3 oblique loading	107.98	138.71
R9	Model 3 lateral loading	190.27	160.17

R= run ***Model 1: 2 Ti implants model***
Model 2: 3 PEEK implants model
Model 3: 4 PEEK implants model

TABE (4) Maximum and Minimum principal stress values for spongy bone in the three model cases of Ti, 3 PEEK and 4 PEEK models.

	Units	MPa	MPa
	Spongy bone	maximum Principal	minimum Principal
R1	Model 1 Vertical loading	1.09	1.57
R2	Model 1 oblique loading	1.27	1.97
R3	Model 1 lateral loading	0.99	2.07
R4	Model 2 Vertical loading	0.92	0.67
R5	Model 2 oblique loading	0.89	0.53
R6	Model 2) lateral loading	0.82	0.56
R7	Model 3) Vertical loading	0.95	0.79
R8	Model 3 oblique loading	0.81	1.12
R9	Model 3 lateral loading	0.82	0.9

R= run ***Model 1: 2 Ti implants model***
Model 2: 3 PEEK implants model
Model 3: 4 PEEK implants model

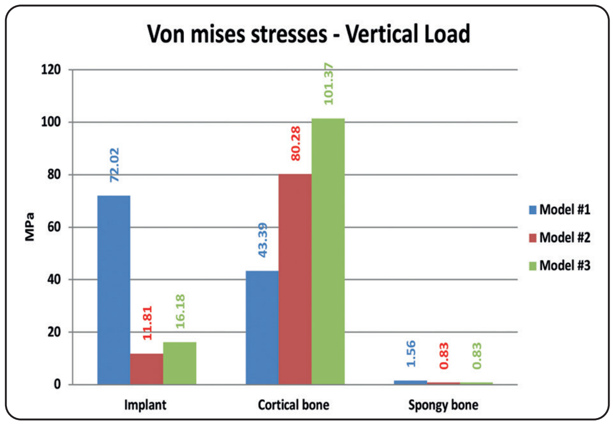

Fig. (2). Bar chart for comparison of Maximum von mises stresses between the three models regarding implant body, cortical and spongy bone after vertical loading.

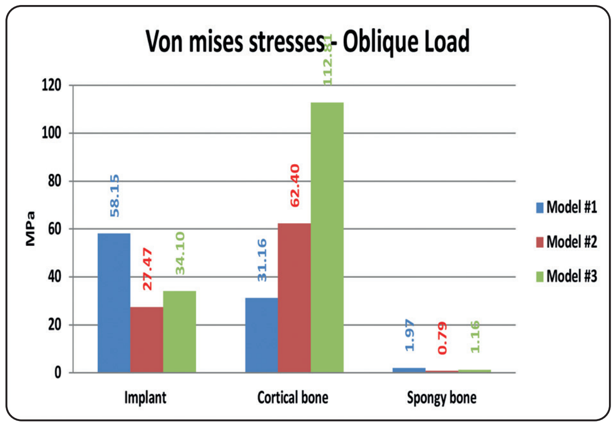

Fig. (3). Bar chart for comparison of Maximum von mises stresses between the three models regarding implant body, cortical and spongy bone after oblique loading.

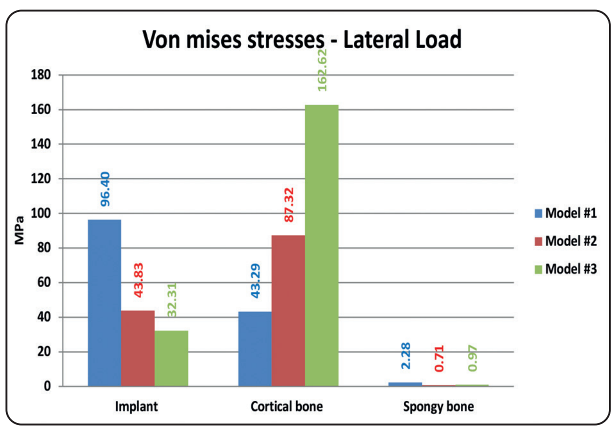

Fig. (4). Bar chart for comparison of Maximum von mises stresses between the three models regarding implant body, cortical and spongy bone after lateral loading.

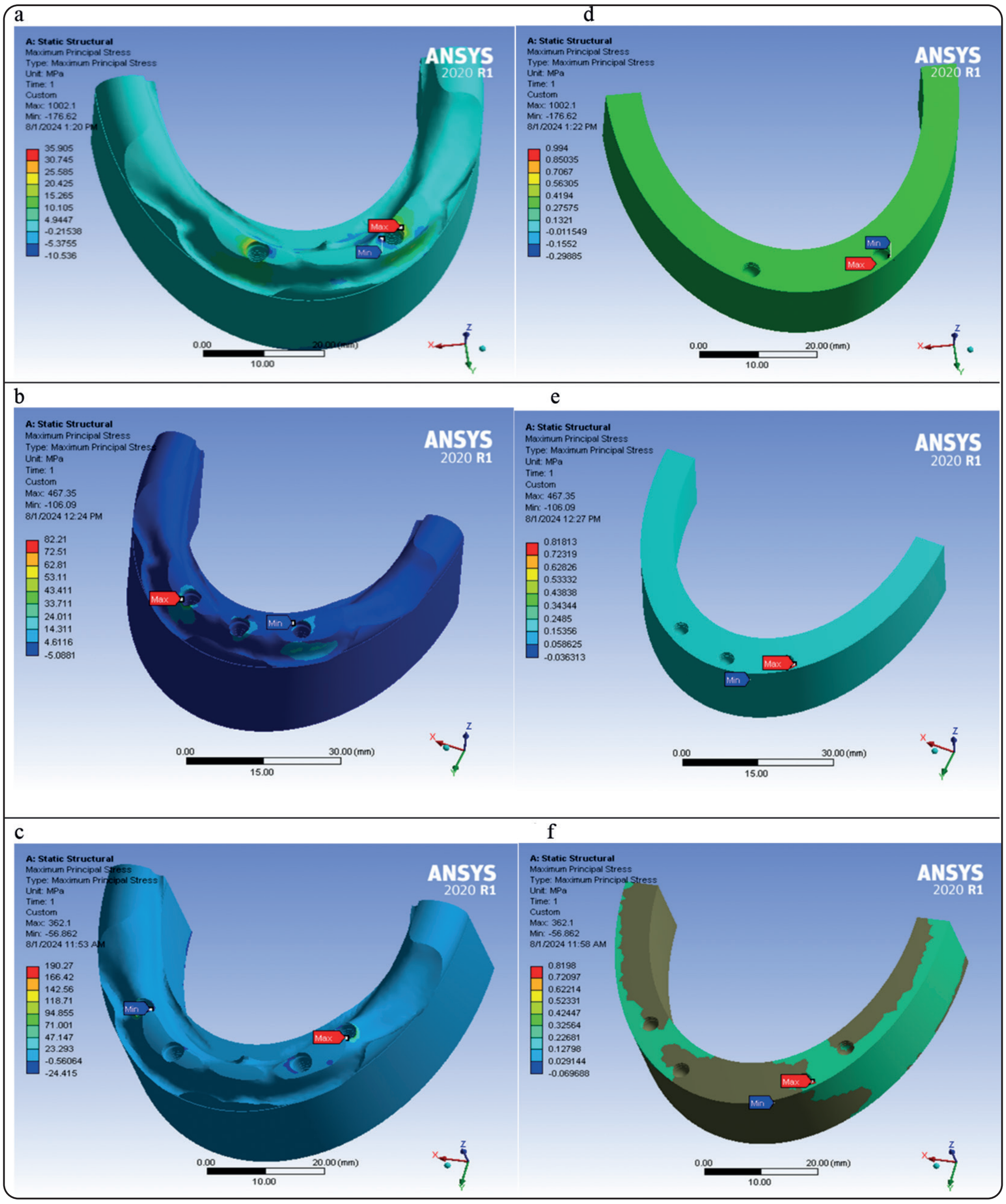

Fig. (5). Maximum principal stresses after lateral loading in cortical bone in: a) model 1, b)model 2 and c)model 3, and in spongy bone in: d) model 1,e)model 2 and f)model 3

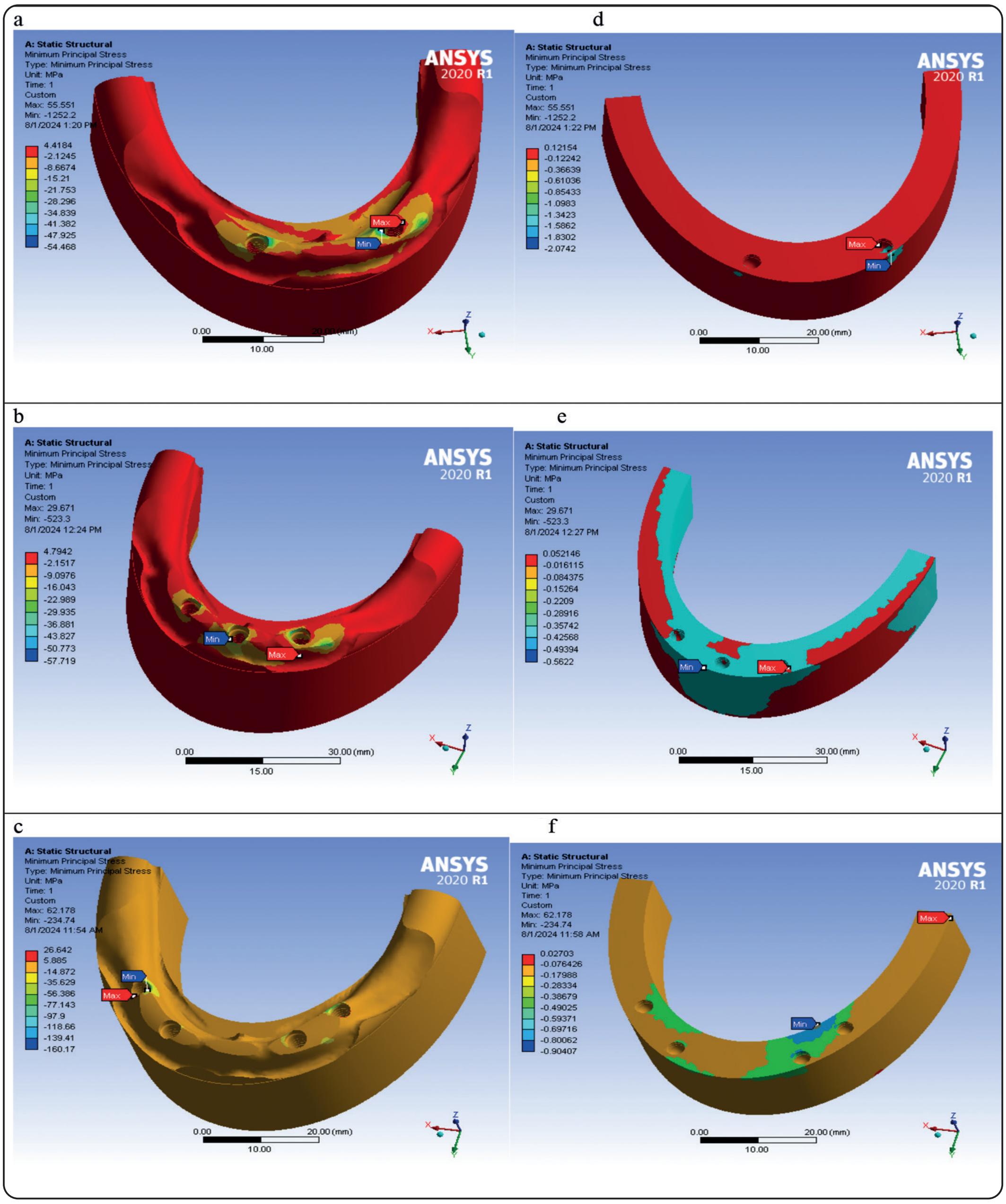

Fig. (6). Minimum principal stresses after lateral loading in cortical bone in: a) model 1, b) model 2 and c) model 3, and in spongy bone in: d) model 1,e)model 2 and f)model 3

DISCUSSION

In the current study three models were developed for mandibular overdenture supported by implants. In first model (model 1) overdenture was supported bilaterally by two titanium alloy implants at canine region. In second model (model 2) overdenture was supported by three PEEK implants, two at canine region bilaterally, in addition to third PEEK implant at midline. While in third model (model 3) four PEEK implants supported overdenture bilaterally at canine and premolar region.

In this study monolithic principle was used for modeling of prosthetic elements, as the same material was used for modeling the implant, gingival former, ball attachment, and the housing matrix in each case model, the two materials were: Titanium alloy Grade V and PEEK. On other hand, the same materials were used for modelling overdenture and O-ring in all cases, which were acrylic resin and plastic-Fluro-rubber respectively.

Analysis of peri-implant bone stresses and strain:

Two failure theories could be followed to predict bone failure, "The maximum-normal-stress (MNS) theory" and "Frost's mechanostat theory" [25] .

However, Due to the brittle and ductile nature of cortical and spongy bone, and also due to the cyclic loading on jaw bone, some authors prefer to follow The maximum-normal-stress (MNS) theory rather than Frost's mechanostat theory [(25,21,24)].

In MNS theory, if one of the three principal stresses became equal or exceeded the strength, bone failure would be expected to occur [26]. MNS theory predicts that failure occurs whenever maximum principal stress $\sigma_1 \geq S_{ut}$ (ultimate tensile strength) or minimum principal stress $\sigma_3 \leq -S_{uc}$ (ultimate compressive strength) [26].

In the present study MNS theory was followed, to predict the bone failure around implants supporting overdenture.

While Von mises stresses were used to predict yielding in implant body, as it is considered a ductile material [21].

Vertical load application:

Cortical bone:

After application of vertical load, and by analysis of von mises stress distribution in peri-implant bone, it was evident that model 3 showed the highest maximum von mises stresses in bone, which was concentrated at crestal cortical bone of the most distal implant (101 MPa), followed by model 2 which showed lower value of maximum von mises stresses (80 MPa) at crestal cortical bone of midline implant, while titanium model (model 1) showed the minimum value of maximum von mises stresses (43.3 MPa), concentrated also at crestal cortical peri-implant bone.

The previous results were in accordance with that of other studies, regarding the concentration of maximum von mises stresses at cortical bone around implant neck [(27,28,29)].

By following the MNS theory, it was observed that maximum principal stresses (MaxPS) and minimum principal stresses (MinPS) in model 1 (titanium model) of cortical bone, were 27.9 MPa and 55.11 MPa respectively. Both values did not exceed the tensile yield strength (100 MPa) and compressive yield strength (140MPa)[21,24] for normal density cortical bone. Using a 1.5 safety factor, the permissible limits would be about (66 and 93MPa) for (MaxPS) and (MinPS) respectively[21]. It was evident that titanium model did not exceed the permissible limit for cortical bone stresses, with satisfactory safety factor.

By analysis of maximum principal stresses (MaxPS) and minimum principal stresses (MinPS) of cortical bone in model 2 (3 PEEK implant model), they were 90.88 MPa and 54.07 MPa respectively, maximum principal stresses (tensile stresses) was located at the labial side of peri-implant cortical bone, around midline implant, on the other hand minimum principal stresses (compression stresses) were located at the distolingual side of peri-implant cortical bone at posterior implant. This can be due to the rotation movement of overdenture upon application of vertical load, taking posterior implants as fulcrum of rotation, with the resilience nature of mucosa, causing downward movement of overdenture posteriorly, and upward movement anteriorly, with concentration of tensile stresses at the labial cortical bone of midline implant.

In model 2, both values of maximum principal stresses (MaxPS) and minimum principal stresses (MinPS) did not exceed the tensile yield strength (100 MPa) and compressive yield strength (140 MPa)[21 24] respectively, for normal density cortical bone. But in case of MaxPS (90.88 MPa) there was a small safety factor value (< 1.5), which carries the risk of fatigue failure of cortical bone and resorption with time [17], especially at the labial side of midline implant due to high tensile stresses, approaching tensile yield strength of cortical bone.

In model 3 (4 PEEK implant model), maximum principal stresses (MaxPS) and minimum principal stresses (MinPS) of cortical bone were 44.3 MPa and 121.45 MPa respectively. (MaxPS) did not exceed the tensile yield strength (100 MPa), and (MinPS) did not exceed the compressive yield strength (140 MPa)[21 24] of normal density cortical bone. However, in case of minimum principal stresses, the value approach the compressive yield strength of cortical bone with low safety factor (<1.5), which was concentrated at the distal side of peri-implant cortical bone of most posterior implant, due to the rotatory movement of overdenture under vertical loading. That carries the risk of fatigue failure of cortical bone and resorption with time [17], especially at the distal side of posterior implant due to high compressive stresses, approaching compressive yield strength of cortical bone.

Spongy bone:

Regarding normal density spongy bone, the value of tensile and compressive stresses that satisfy safety factor of 1.5 are (6.5 and 10.5 MPa) respectively [21], by analysis of maximum and minimum principal stresses of spongy bone in the three models, it was found that they were highest in titanium model (1.09,1.57 MPa) respectively. In general, the maximum and minimum principal stresses of spongy bone in the three models were far below the tensile and compressive yield strength of normal density spongy bone, satisfying safety factor > 2.5[23].

Implant body:

By analysis of maximum von mises stresses in implants bodies of the three models, they were found to be always located at implant neck, which is in accordance with the results of other studies[25,28,30] . Also, it was found that maximum von mises stresses in titanium implants in model 1 (72 MPa), were far below the yield strength or the fatigue limit of Titanium Grade V, which are about 860-870 MPa and 500 MPa respectively [17,5].

Regarding PEEK implants in model 2 and 3 maximum von mises stresses were 11.81 and 16.18 MPa respectively, which also are far below the yield strength of PEEK polymer (95 MPa) [22], with factor of safety > 2.5 .

So, it is not expected a fatigue failure or yielding of PEEK implants in both model 2 and 3, under vertical loading.

Oblique loading application:

Cortical bone:

After application of oblique load, and by analysis of maximum von mises stresses distribution in peri-implant bone, they showed the same distribution pattern as in vertical load application, by concentration of maximum values at cortical bone. The highest values were in model 3 (112 MPa), and the minimum were in model 1 (31.16 MPa).

By following the same systematic analysis of maximum and minimum principal stresses of per-implant cortical bone as in case of vertical loading, it was found that MaxPS (26.69 MPa) and MinPS (35.91 MPa) values in peri-implant cortical bone of titanium model, were far below tensile and compressive yield strength of normal density cortical bone [23].

In Model 2 (3 PEEK implant model) the MaxPS (56.93 MPa) and MinPS (53.9 MPa) values were higher than those of titanium model, but still lower than tensile and compressive yield strength of normal density cortical bone, with safety factor >1.5 in tensile stresses, and > 2.5 in compressive stresses.

In model 3 (4 PEEK implant model) the MaxPS (107.9 MPa) and MinPS (138.71 MPa) values were the highest in the three models, exceeding the tensile yield strength and approaching the compressive yield strength of normal density cortical bone., which carries the risk of yielding and subsequent resorption of peri-implant cortical bone [25,23] .

Spongy bone:

As previously described in vertical load application, and by analysis of maximum and minimum principal stresses of spongy bone in the three models, it was found that they were highest in titanium model (1.27,1.97 MPa) respectively. In general, the maximum and minimum principal stresses of spongy bone in the three models were far below the tensile and compressive yield strength of normal density spongy bone, satisfying safety factor > 2.5 [23].

Implant body:

By analysis of maximum von mises stresses in implants bodies of the three models, they were found to be always located at implant neck, like vertical load scenario. Also, it was found that maximum von mises stresses in titanium implants in model 1 (58.15 MPa), were far below the yield strength or the fatigue limit of Titanium Grade V [17] [5].

Regarding PEEK implants in model 2 and 3 maximum von mises stresses were 27.47 and 34.1 MPa respectively, which were higher than corresponding values in vertical loading scenario, but still far below the yield strength of PEEK polymer (95 MPa) [22], with factor of safety > 2.5 .

Lateral load application:

Cortical bone:

After application of lateral horizontal load, and by analysis of maximum von mises stresses distribution in peri-implant bone as before, they showed the same distribution pattern as in vertical and oblique load application, by concentration of maximum values at cortical bone. The highest values were in model 3 (162 MPa) exceeding cortical bone yield strength [22] , and the minimum were in model 1 (43.29 MPa).

By observing maximum and minimum principal stresses, it was found that MaxPS (35.9 MPa) and MinPS (54.47 MPa) values in peri-implant cortical bone of titanium model, were far below tensile and compressive yield strength of normal density cortical bone [23].

Model 3 recorded the highest MaxPS (190.27 MPa) and MinPS (160.17 MPa) values, which far exceeding the tensile and compressive yield strength of normal density cortical bone, which confirms that under horizontal lateral loading cortical bone would exhibit yielding and resorption [27]. These results are in accordance with results of other studies, that showed that nonaxial loading causing high stresses, and is related to peri-implant marginal bone loss, osseointegration failure, and failure of implants and prosthetic components [27] [17] .

Model 2 showed moderate values of MaxPS (82.2 MPa) and MinPS (57.72 MPa) values, which demonstrated that tensile stresses are higher than compressive stresses, with safety factor <1.5, while compressive stresses are far below compressive yield strength with safety factor > 2.3.

Spongy bone:

As in vertical and oblique loading scenarios, maximum and minimum principal stresses of spongy bone in the three models, were found to be highest in titanium model (0.99 ,2.07 MPa) respectively. In general, the maximum and minimum principal stresses of spongy bone in the three models satisfying safety factor > 2 [23].

Implant body:

By analysis of maximum von mises stresses in implants bodies of the three models, they showed the same distribution pattern, by locating at the implant body neck area. Titanium implant maximum von mises stresses (96.4 MPa) were far below the yield strength or the fatigue limit of Titanium Grade V [17,5].

Regarding PEEK implants in model 2 and 3 maximum von mises stresses were 43.83 and 32.3 MPa respectively, which were below the yield strength of PEEK polymer [22], with factor of safety > 2.

Concentration of stresses at cortical bone around implant neck, can be attributed to the higher elastic modulus of cortical bone than spongy bone, which makes peri-implant cortical bone acts as fulcrum, bearing more stresses especially in case of non-axial loading [25].

Schwitalla et al studied the biomechanical effect of using monolithic principle in making implant-abutment assembly entirely from PEEK or titanium, they concluded that PEEK caused more cortical bone stresses than titanium, due to the lower elastic modulus of PEEK [22]. These results are in accordance with that of the current study, which explains the higher stresses of peri-implant cortical bone in PEEK models than those of titanium model.

By comparing model 2 (3 PEEK implants) to model 3 (4 PEEK implants), it was found that model 2 showed more favorable bone stress distribution, without exceeding the critical yield strength limit of cortical bone, which indicates the importance of the support offered by midline implant in model 2, which limits the deformation of PEEK implants, especially under oblique and lateral loading, and that led to lower stresses transferred to cortical bone, than in case of 4 PEEK implants model.

In the current study, it is evident that distribution and positions of implants supporting overdentures are far more important than their number, this result is in accordance with that of Hong et al, who stated that The lowest stresses accompanied by best stability of implants in mandibular two-implants supported overdentures, were obtained when implants were inserted in lower lateral incisors regions, with short attachments and positioned parallel to the long axes of the teeth, in comparison to other positions and attachments in canine and premolar sites[31].

Also, Anwar et al found by using FEA that using two implants in the canine region supporting lower overdenture, would show better von mises stresses distribution rather than using four implants [32], which supports results of the current study.

Although, three PEEK implants model (model 2) was promising and showed better stresses distribution in peri-implant bone rather than 4 PEEK implants model (model 3), but it is still inferior to titanium model (model 1). So, using 3 PEEK implant models instead of titanium needs more research studies, using other PEEK implants' dimensions, to decrease cortical bone stresses [33], especially in the labial side of midline implant.

It must be taken into consideration that stress analysis in this study was carried out by using models of normal density bone. Using bone models with weak density could result in different stress distributions at peri-implant bone [21 34].

CONCLUSIONS

Within limitations of this study, it was concluded that:

1- Complete Mandibular overdenture supported by three PEEK implants, with triangular distribution (2 in canine regions, 1 in midline), may be a promising treatment option for restoring edentulous mandible, with normal density bone.

2- The previous design showed critical high tensile stresses in the cortical bone labial to midline implant approaching bone yield strength, with safety factor < 1.5.

3- Complete Mandibular overdenture supported by four PEEK implants (2 in canine region, 2 in premolar area), is not a promising treatment option due to extremely high stresses induced in cortical bone (> bone yield strength), especially in non-axial loading conditions.

Recommendations:

- Future studies are needed for biomechanical analysis of Mandibular overdenture supported by three PEEK implants (model 2), but with different dimensions of midline implant (length and/or diameter), to decrease labial cortical bone stresses.

List of abbreviations:

1- FEA: Finite element analysis

2- MaxPS: Maximum principal stresses

3- MPa: Mega Pascal

4- MinPS: Minimum principal stresses

5- PEEK: Poly ether ether ketone

Declarations:

Ethics approval and consent to participate:

This research doesn't require ethical approval and followed the Helsinki declaration.

Consent for publication:

Not applicable

Availability of data and material:

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Competing interests:

The authors declare that they have no conflict of interests.

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Authors' contributions:

1. SE: created the design of the study, interpreted results of finite element analysis, and made a major contribution in writing and editing.
2. YA: participated in creating the design and editing of the study had a major contribution in writing the review of literature.
3. MI: participated in creating the design of the study, performed all the finite element analysis practical work, interpreted the results and had a major contribution in writing the methods and results.
4. EE: revision of the interpretation of results and final editing of manuscript.
5. RA: revision of the interpretation of results and final editing of manuscript.

- All authors read and approved the final manuscript

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