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Original Article

Comparison of the biomechanical effect of distal implants placed at different angles in the all-on-four technique: A nonlinear finite element analysis

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ABSTRACT

Introduction: The “All-on-four” technique addresses this by placing two vertical implants in the anterior region and two posterior implants angled up to 45°. This study evaluates stress distribution on bone, implants, abutments, gingiva, and prostheses based on posterior implant angulation, using both standard and angled neck implants. Additionally, angled neck implants were used alongside standard implants.
Methods: To evaluate the biomechanical stress and displacement behavior of implants placed at 15°, 30°, 45°, and 30° neck-angled in the interforaminal region of using the All-on-four technique, under a 200 N masticatory force on bone, implant, abutment, and prosthesis, using the FEA method with a nonlinear solver.
Results: The stress values measured in the neck region of the angled implant and abutment placed in the distal region were highest in model IV (305 and 420 MPa), followed model III (282 and 359 MPa), model II (192 and 337 MPa) and lowest in model I (177 and 225 MPa), respectively. The mean elemental von Mises stress in the mandibular bone region where the implant was placed was highest in model I (56 MPa) and lowest in model III (40.4 MPa).
Conclusion: As the angle of insertion of the implant into the bone increases, the biomechanical stress value on the implant and abutment also increases. Among the models, the lowest von Mises stress values on the implant and abutment were measured in model I and model II. Models with low stress values can be recommended for patients with clinical conditions and biomechanical risk factors.
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1. Introduction

In 2003, Malo et al. introduced a novel concept known as the "All-on-four" technique to facilitate the placement of fixed prostheses in patients with excessively atrophic crests. In this approach, two implants are vertically positioned in the anterior region within the interforaminal space, while two posterior implants are inclined distally angles that can increase up to 45°. The inclination of the distal implants serves to reduce cantilever length and enhance the efficiency of masticatory function, allowing for the fixed prostheses [1,2].

Advantages, such as use of fewer implants compared to conventional methods and the ability to immediate loading protocols, have rendered all-on-four systems very popular, leading to a demand for various studies to enhance their mechanical properties. Different designs in the macro and micro structures of implants constitute some of these studies. Medentika®(MEDENTiKA GmbH, Hügelsheim, Almanya) has developed an implant neck design with the same angle as the implant placement angle in the neck area for use in All-on-four systems. The company has produced Quattrocone 30 implants, which end at the same level as the bone despite being placed at an angle. Consequently, the difference in mesial and distal bone levels caused by the angled application of standard implants is minimized. This has led to the avoidance of incorrect positioning of multiunit abutments, the need for additional surgical procedures such as bone reduction, and aesthetic problems [3].

In addition to these changes in implant designs, biomechanical forces, which are essential for both long and short-term success, are thoroughly examined in various studies. The impact of these biomechanical forces on the implant and bone can be examined through finite element analysis (FEA). The FEA is an engineering technique employed to calculate the amount of stress and deformation in order to solve complex problems and it is an important numerical method used in dentistry. FEA can be used to evaluate the amount of stress change and displacement that occurs in different anatomical

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structures, such as hard and soft tissues (bone, teeth, prostheses, and dental materials)[4–9].

In this study, considering all factors, we evaluated with FEA the stress and displacement measurements on the bone, implant, abutment, mandible, mucosa/gingiva and prosthesis of implants placed distally in the interforaminal region at 15°, 30°, 45° angles in mandibular edentulous patients to be treated with the All-on-Four concept. Additionally, the difference between neck-angled 30° and standard implants was also evaluated.

2. Material and methods

As part of the BodyParts 3D project, a model of the mandible of a male skull (completely edentulous) was downloaded from open source in STL format (National bioscience database center 2021). Using Ansys Workbench (ANSYS Inc. Houston, PA, USA) software, a 3D model of the implant with the same diameter and length, with the neck-angled 30° (4.3 × 13 mm neck-angled implant at 30°) / (Quattrocone 30 implant, Article No: 4–01–03, Medentika, Germany) and straight (4.3 × 13 mm straight implant) / (Quattrocone implant, Article No: 3–01–09, Medentika, Germany) was designed (Fig. 1A).

In the edentulous mandible model, the thickness of the cortical bone is 2 mm superior, 1 mm buccal and lingual, and the inner parts are designed as trabecular bone. The final model illustrated a fixed prosthesis supported by four implants utilizing the All-on-four technique for an edentulous mandible. Two anterior implants were placed bilaterally and vertically in the lateral incisor regions, while the two posterior implants were positioned with a distal inclination in the second premolar regions. For comparative analysis, the apex of the posterior implants was mesialized to achieve various configurations with inclinations of 15°, 30°, and 45° Additionally, 4 distinct All-on-four configurations were obtained by incorporating a 30° neck angled implant to address anatomical needs. One cylindrical multi-unit titanium abutments were modeled and placed on the vertical implants and three angled multiunit abutments were placed on the tilted implants.

The mucosa was modeled with a thickness of 2 mm depending on the mandible surface geometry. Mandible, mucosa, prosthesis, implant and abutment design were independently included in the overall model. All the prepared models were combined on the same coordinate system into a single model. A symmetrical model of the mandible was then created for finite element analysis. To ensure standardization between models and eliminate design-related errors, the abutments were designed with equal diameters and lengths, compatible with the implant angles to be used.

2.1. Boundary conditions

The temporomandibular joint region of the mandible was fixed. The nodal points in the temporomandibular joint region (X, Y and Z axes) were considered fixed to prevent translational and rotational movement.

In each model, a force of 200 N was exerted at a 30° angle to the long axis of the first molar. The force was applied from the lingual to the buccal ridge of the buccal tubercle of the tooth in the direction from the lingual to the buccal. To enhance the accuracy of the analysis results, the mandible model included masticatory muscle forces (posterior temporalis, middle temporalis, deep masseter, superfacial

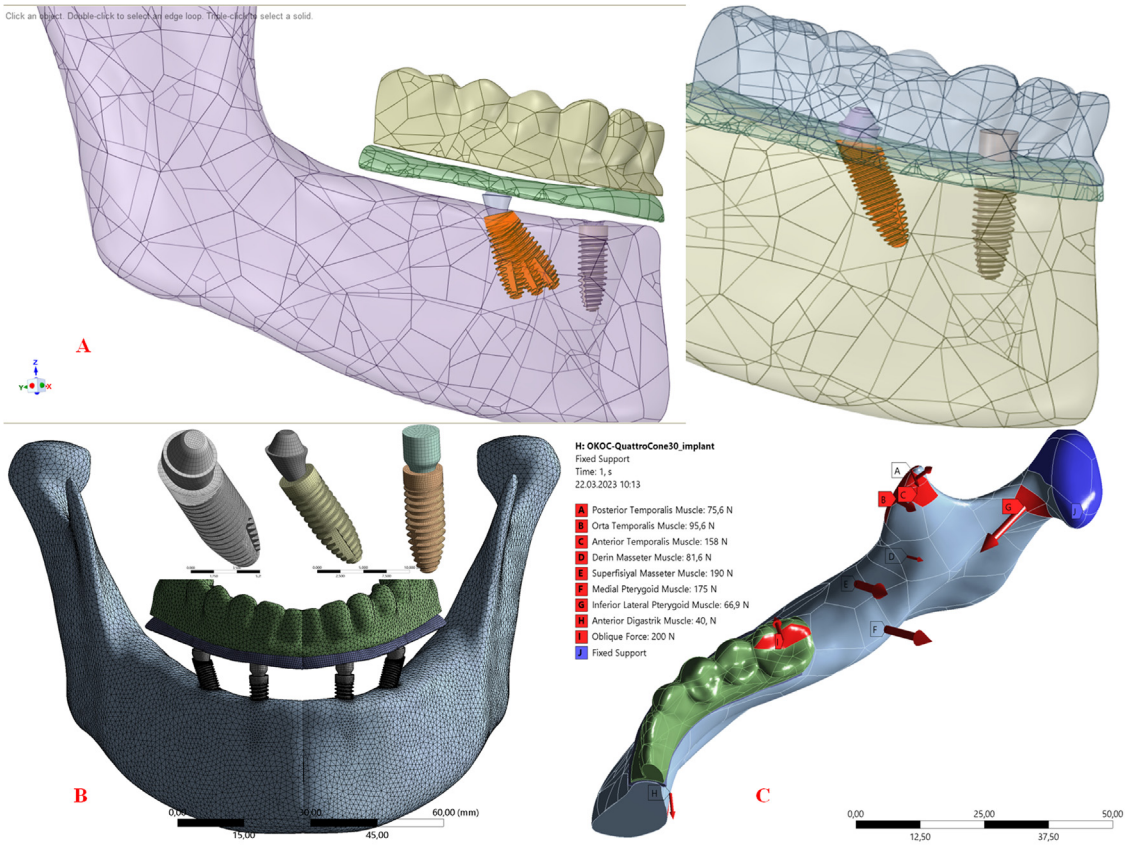


Fig. 1. A, Symmetrical model of the anatomical structure of the All-on-four model, consisting of mandible, straight implant-placed at various angles (0°, 15°, 30°, 45°) and multi-unit abutment, neck-angled 30° implant, mucosa and prosthesis; **B**, Front view of the anatomical structure of the All-on-four model divided into 10-node quadratic tetrahedral and 20-node quadratic hexahedral mesh element types; **C,** A force of 200 N at an angle of 30° to the long axis of the first molar (oblique) and masticatory forces were applied to the as boundary conditions.

Table 1
Finite element model's material properties.

Material properties (Mpa)	Elastic modulus	Poisson's ratio	Shear modulus
Cortical mandibular bone	Ex: 12,600	Vxy: 0.25	Gxy: 5700
	Ey: 19,400	Vyz: 0.39	Gyz: 5700
	Ez: 12,600	Vxz: 0.30	Gxz: 4850
Cancellous bone	Ex:1148	Vxy: 0.32	Gxy: 434
	Ey: 1148	Vyz: 0.05	Gyz: 68
	Ez: 210	Vxz: 0.05	Gxz: 68
Acrylic resin	3000	0,35	
Mucosa	1	0.37	
Implant and Abutment (Titanium)	105,000	0,37	

MPa: Megapascal.
Ex, Ey, Ez: Elastic modulus in three directions.
Vxz, Vyz, Vxz: Poisson's ratio in three directions.
Gxy, Gyz, Gxz: Shear modulus in three directions.

masseter, median pterygoid, inferior lateral pterygoid, anterior digastric muscle) (Fig. 1C). The force values applied to the mandible by the masticatory muscles are given in Table 4 [10].

Frictionless contact between the mucosa and prosthetic surfaces (allowing a very small amount of sliding over each other) was defined. Bonded contact was defined between the implant and the surfaces between the mandible and the abutment, and between the abutment and the prosthesis and mucosa.

Mandible (cortical and cancellous bone), the implant and abutment (titanium) were considered anisotropic materials. Conversely, the prosthesis and mucosa were assumed to be homogeneous and isotropic. An anisotropic material property was assigned to better describe the actual behaviour of the bone and to approximate the correct result. The material properties of each component are shown in Table 1 [11,12].

Coordinates are defined as x-axis sagittal plane, y-axis vertical plane and z-axis transversal plane. In the models, the displacement values have been measured in mm and the von Mises stress values have been measured in MPa. Each deformation state and stress value is represented using a different color scale band. Geometric nonlinear theory, nonlinear contact theory, and nonlinear materials methods were used to evaluate displacements and von Mises stress distribution in transient structural analysis (dynamic analysis). Displacement and stress values were measured on the same element in all models using a probe in the ANSYS software.

2.2. Finite element model

The mandible were divided into elements with dimensions of 1.3 mm, the prosthesis model 1 mm and the elements were of type 10-node, quadratic tetrahedral. The implant was subdivided into 0.2 mm elements, the abutment into 0.4 mm elements, and the mucosa into 0.5 mm elements, and the mesh was of the quadratic hexahedral type with 20 nodes. The entire model was divided into a total of 1,072,716 nodes and 616,193 elements (Table 2, Fig. 1B).

In the mandible, the bone surface on which the implant sits (the region of the screw grooves) and in the implant model (the screw threads) were divided into a mesh size of 0.1 mm. Element, node, and mesh size values were set to be approximately the same for the four models, and the average mesh skewness element quality convergence value was 0.3. Mesh convergence was performed in the mandible (on the bone surface where the implant sits), implant and abutment. Table 3 shows the spectrum of the skewness mesh metrics (Fig 4).

It was observed that the element mean stress values of the elements in the region of maximum stress did not change >1 % in the mesh convergence interval (although the mesh size was reduced).

3. Results

3.1. Stress distribution

The highest mean elemental von Mises stress value measured on the angled implant and abutment was found in Model-IV and the lowest in Model-I.

The lowest mean elemental von Mises stress value measured on the straight implant and abutment placed in the anterior region was found in Model-I and the highest in Model-IV.

The von Mises stress value in the neck region of the distal multiunit abutment was measured highest in Model-IV (420 MPa), followed by Model-III (359 MPa), Model-II (337 MPa), and Model-I (225 MPa), respectively. The stress values measured on the neck region of the angled implant were highest in Model-IV (305 MPa), followed by Model-III (282 MPa), Model-II (192 MPa), and lowest in Model-I (177 MPa) (Table 5, Fig. 3A, B, C, D, Videos 1–4).

The stress values measured in the neck region of the straight implant and abutment, respectively, were highest in Model-IV (77.8 and 71.5 MPa), followed by Model-III (75.3 and 65 MPa), Model-II (60.2 and 40 MPa) and lowest in Model-I (41.6 and 31.5 MPa) (Table 5, Fig. 3A, B, C, D, Videos 1–4).

The mean elemental von Mises stress values in the mandibular bone region where the implant was placed were highest in Model-I (56 MPa), followed by Model-II (45.8 MPa), Model-IV (44.1 MPa), and smallest in Model-III (40.4 MPa) (Table 5, Fig. 3A, B, C, D, Videos 1–4).

The average elemental von Mises stress distribution values for the mandible, implant, abutment and prosthetic structures in all models are shown in Table 5.

3.2. Amount of displacement

The maximum total displacement was measured at the buccal apex of the first molar in all models. Model-II exhibited the highest displacement at 0.82 mm, followed by Model-III at 0.74 mm, Model-IV at 0.71 mm, and Model-I at 0.69 mm (Fig. 2A, B, C, D).

The coronoid process region showed the highest amount of displacement in the mandible, measuring 0.50 mm in Model II and 0.48 mm in Model III. In Model I and Model IV, the displacement was the same at 0.45 mm each. The displacement measured in the

Table 2
Finite element model's element, nodes, mesh size and average skewness element quality convergence values.

	Average skewness value	Nodes	Element	Mesh size (milimeters)	Mesh element type
Mandible	0.26	690,744	478,460	1,3	Tetrahedral
Acrylic Resin	0.24	54,132	36,035	1	Tetrahedral
Mucosa	0.5	35,068	10,285	0,5	Hexahedral
Straight Implant	0.6	109,849	34,620	0.2	Hexahedral
Neck-angled Implant	0.6	172,094	54,505	0.2	Hexagonal
Multiunit Abutment	0.2	10,829	2288	0.4	Hexahedral

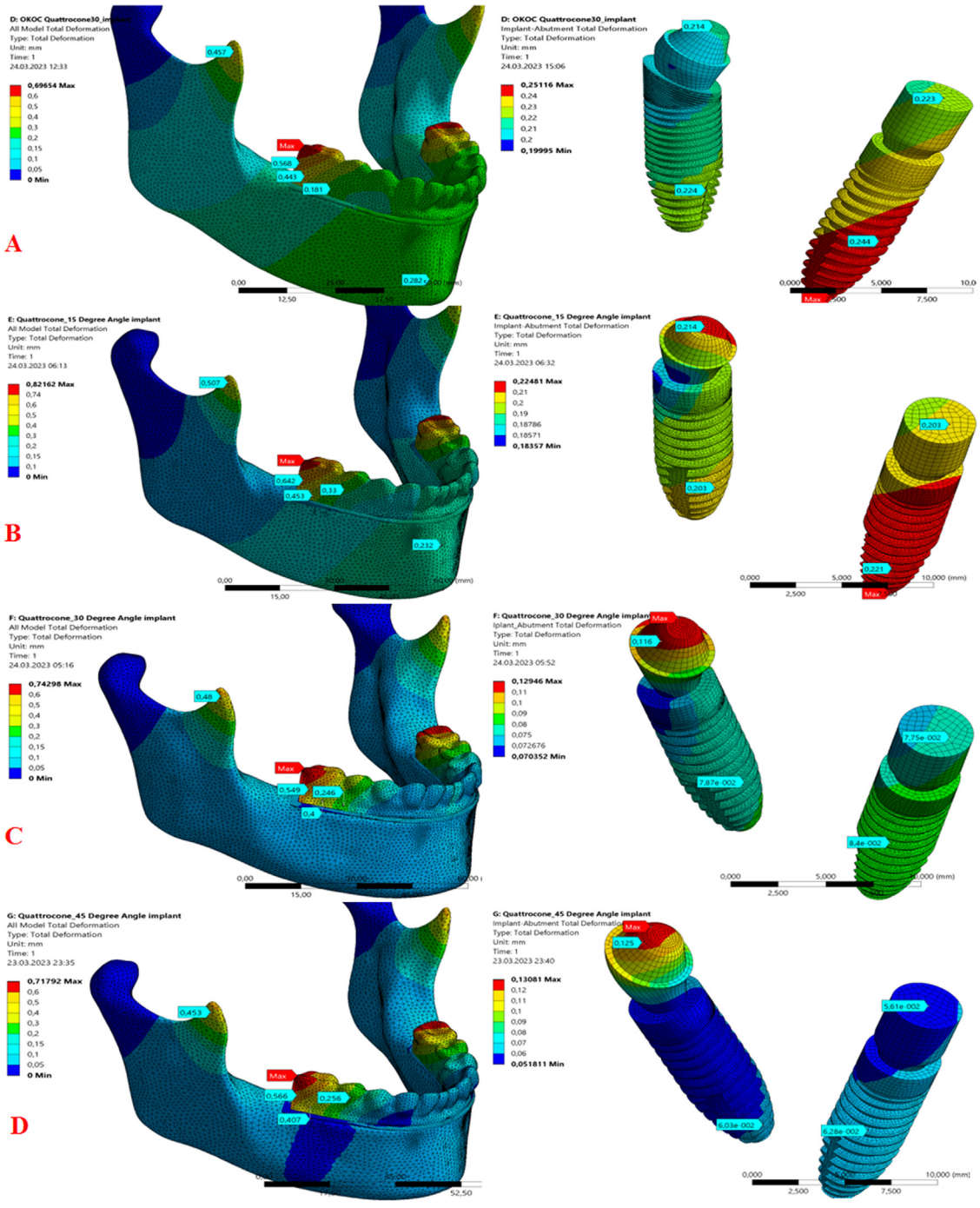


Fig. 2. Mandible, straight implant and multi-unit abutment placed at 0°, 15°, 30°, 45° angles, neck-angled 30° implant, total displacement of mucosa and prosthesis anatomical structure (mm). **A**, Model-I: neck-angled 30° implant and abutment; **B**, Model-II: Straight implant and abutment placed at a 15° angle; **C**, Model-III: Straight implant and abutment placed at a 30° angle; **D**, Model-IV: Straight implant and abutment placed at a 45° angle.

Table 3
Skewness mesh metrics spectrum.

Excellent	Very good	Good	Acceptable	Bad	Un acceptable
0–0.25	0.25–0.50	0.50–0.80	0.80–0.94	0.95–0.97	0.98–1.00

Table 4
Masticatory muscle forces (N).

Masticatory muscles	Force (N)	Fx	Fy	Fz
Posterior temporal	75,6	64,63	15,72	35,83
Middle temporal	95,6	47,80	21,22	80,01
Deep masseter	81,6	29,21	44,55	61,85
Superficial masseter	190,4	79,77	39,41	168,31
Medial pterygoid	174,8	65,20	84,95	138,26
Inferior lateral pterygoid	66,9	50,64	−42,14	−11,64
Anterior digastrik	40	37,60	9,76	−9,48

Table 5
Mean distribution of elementary stresses (von Mises and first principal stresses) (MPa) in the mandible, implant, abutment, prosthesis and gingiva as a result of an oblique 200 N chewing force applied to the first molar in all model.

	Model-I	Model-II	Model-III	Model-IV
Anatomic structure	Von Mises Stress (MPa)	Von Mises Stress (MPa)	Von Mises Stress (MPa)	Von Mises Stress (MPa)
Distal implant bone site	56.7	45.8	40.4	44.1
Straight Implant	41.6	60.2	75.3	77.8
Straight Multiunit Abutment	32.5	40	65	71.5
Distal Implant	177	192	282	305
Distal Multiunit Abutment	225	337	359	420
Prosthesis	65	54.6	42.9	39.2
Gingiva	0.187	0.143	0.205	0.168

anterior part of the mandible was highest in Model I (0.28 mm), followed by Model II (0.23 mm), and then by Model III and Model IV (0.15 mm) which had the same displacement (Fig. 2A, B, C, D).

The straight implant positioned at the anterior incisor level showed the maximum total displacement in Model-I (0.25 mm, max) and Model-II (0.22 mm, max). In Model-III (0.08 mm) and Model-IV (0.06 mm), the displacement value was smaller.

In both Model-I and Model-II, the largest total displacement measured in the straight and angled abutment placed at the anterior incisor alignment was approximately the same, at 0.2 mm. In both Model III and Model IV, the maximum total displacement recorded at the angled abutment was 0.13 mm. At the straight abutment, Model III recorded a displacement of 0.077 mm, while Model IV was measured 0.056 mm (Fig. 2A, B, C, D).

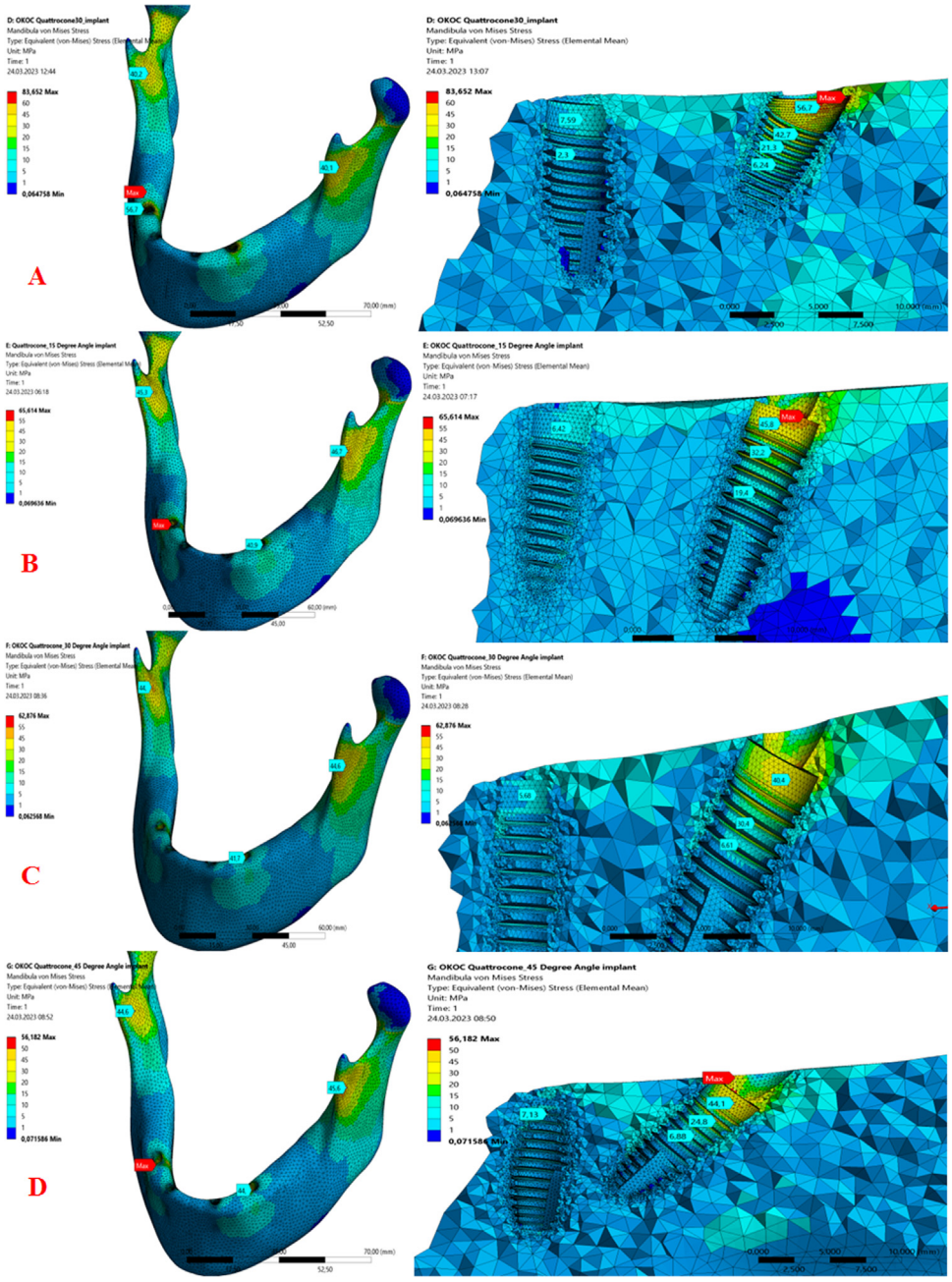


Fig. 3. **A**, Model-I; **B**, Model-II; **C**, Model-III; **D**, Model-IV; The von Mises stress (MPa) values measured in the mandible and in the bone region where the implant was placed.

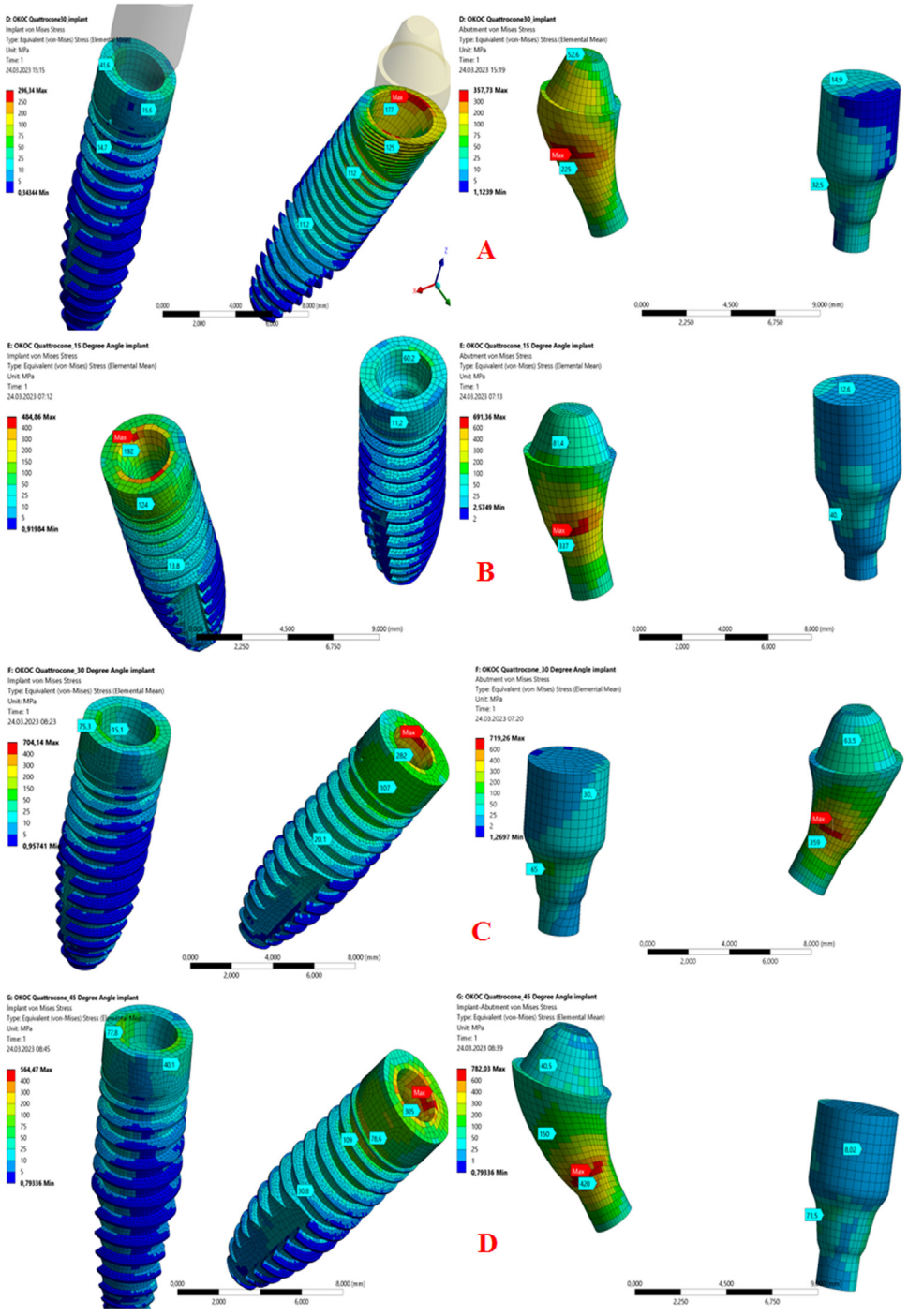


Fig. 4. The von Mises stress (MPa) values measured on a straight implant placed at an angle of 0°, 15°, 30°, 45°, on a multi-unit abutment and on a neck-angled 30° implant. **A**, Model-I; **B**, Model-II; **C**, Model-III; **D**, Model-IV.

4. Discussion

In edentulous patients, traditional removable prostheses offer only 10 % of the functionality compared to natural teeth, while 2 or 4 implant-supported overdenture prostheses provide approximately 60 % functionality. Fixed prostheses utilizing the All-on-four treatment concept significantly enhance functionality, delivering up to 70 % of the functionality of natural teeth [13]. The All-on-four dental implant treatment, pioneered by Maló et al. in 2003, involves the placement of four implants supporting fixed prosthetic restorations, providing both comfort and financial advantages to patients, as they can receive their prostheses in the same session with fewer implants [14]. Studies evaluating All-on-four concept implants have assessed indications, surgical procedures, prosthetic stages, and complications. These investigations have demonstrated a remarkable survival rate of 99.8 % for these implants over a minimum of 24 months, indicating the efficacy of this approach as a successful alternative to regenerative methods, which often entail higher morbidity and costs [15].

When implant placement is undertaken, even if there is sufficient vertical bone, deficiencies or irregularities may be encountered horizontally. Following socket healing post-extraction, greater resorption typically occurs in the buccal region compared to the lingual region.

Approximately 50 % of this resorption transpires within the initial year, leading to irregularities at the crest [16–18]. Studies investigating these irregular crests have revealed that when implants are positioned with regard to either the lingual or buccal bone, aesthetic issues arise or necessitate bone reduction. Consequently, the necessity to develop and utilize implants featuring a sloping neck region has become apparent [19]. Schiegnitz et al. conducted an evaluation of 238 implants featuring a buccolingually angled neck, assessing the success and survival of both soft and hard tissues over a follow-up period of up to 2 years. They reported a mean inter-proximal marginal bone loss of 0.30 ± 0.6 mm, indicating a high level of bone stability in these neck-angled implants [20]. Similarly, in a study involving 65 patients with buccolingual crest discrepancies ranging from 2 mm to 5 mm, the mean change in interproximal bone levels was found to be 0.54 mm, with minor changes observed in both hard and soft tissues during clinical examinations and radiologic evaluations [19]. These findings underscore the functional efficacy of implants with a beveled configuration, demonstrating a high survival rate after 2 years. The beveled implant neck design contributes to the support of both hard and soft tissues around the implant neck, facilitating the restoration of a physiologically appropriate peri-implant keratinized mucosa in patients with compromised peri-implant soft tissue conditions.

Biomechanical factors play a crucial role in determining the survival rate and clinical success of dental implants. Unlike natural teeth, implants lack periodontal ligament spacing, thus transmitting occlusal forces directly to the surrounding bone. Therefore, ensuring a homogeneous distribution of these forces is paramount. While marginal bone loss of 2 mm in the first year and 0.2 mm in subsequent years is considered normal in implant treatments [21], continual exposure to uneven high forces can exacerbate this bone loss, leading to pathological conditions [22]. Excessive stresses exerted on dental implants during chewing can also contribute to bone resorption. Consequently, it is crucial to identify areas of concentrated stress in the bone surrounding the implant [23]. Among the various methods available to analyze stress distribution in peri-implant bone tissue, finite element stress analysis stands out as one of the most widely utilized, offering the capability to examine stress and strain measurements in three dimensions [24].

The FEA method is an accurate simulation tool to evaluate surgical procedures performed on various anatomical structures in the all-on-four technique. Furthermore, FEA is often used in implant surgery to reveal the most accurate position of the implant with the optimum insertion angle between bone and implant depending on the resistance of the structures under different loading conditions.

The aim of this study was to evaluate the stress and displacement biomechanical behaviour of bone, implant, abutment and prosthesis under 200 N masticatory force due to variations in implant angulation in the distal region of the interforaminal space in mandibular edentulous patients treated with the all-on-four concept using the nonlinear FEA method. Straight implants from Medentika (MEDENTiKA GmbH, Hügelsheim, Germany) were placed at angles of 0°, 15°, 30°, and 45°, while the Quattrocone30 implant from the same company, featuring a neck angle of 30°, was also positioned at a 30° angle.

To represent the clinical situation of an adult patient, this distal implant FE model, placed at different inclinations, includes a mathematical model based on the anatomical structures with the mandible to rationalize the All-on-four treatment.

In their FEA studies, Cervino et al. reported the yield strengths for titanium and cortical bone as 485 MPa and 115 MPa, respectively [25].

Among the models, the highest von Mises stress value on the implant and abutment was measured in model-IV (305 MPa and 420 MPa, respectvely) and model-III (282 MPa and 359 MPa, respectvely) respectively. The highest stress values measured on the distal implant and abutment were below the yield strength of the titanium material in all models and were within the safe zone. Particularly in model-IV, cracks or fractures in the neck area of the distal implant and abutment are to be expected if the masticatory force or bruxism increases too much.

The stress values measured on the implants and abutments placed in the distal region were found to be much higher than the straight implants and abutments placed in the anterior region. This is because the implants and abutments placed in the distal region are in the region of the masticatory force.

The von Mises stress values measured on the bone in the region where the distal implant was placed in the mandible are approximately similar for Models II, III, and IV. For model I, this stress value was measured slightly higher. As these stress values are smaller than the yield strength of the bone, they are in the safe zone and fracture or cracking of the bone is not expected.

In the literature, Sannino compared the stress values of distal implants placed at different angles (15°, 30° and 45° inclination) in the maxilla only at the implant-bone interface under four different loading conditions. The results showed that the distal implant placed at 15° and 30° had the lowest stress value at the bone site and the implant placed at 45° had the highest and critical stress value at the bone site [26]. Begg et al. used photoelastic stress analysis to investigate the stress distributions around distally angled implants at 0°, 15°, 30° and 45° of the all-on-four system under different loading conditions. While no significant difference in stress distributions was observed between implants placed at 15° and 30°, a significantly increased stress level was observed in the 45° implant model [23]. Boukhlif et al. examined the distribution of stress in the bone-implant interface of implants placed at varying angles (0°, 15°, 30°) under a loading condition of 10 MPa. The highest stress value was observed in the bone region of the implant placed at 0° inclination, while the lowest stress value was recorded around the implant bone at 15° and 30° inclinations [27]. Melo and Francischone, investigated the stress distribution on bone, implant and abutment of implants of two different diameters placed at an angle of 30° and under a loading condition of 100 N in the all-on-four technique. The highest stress value was observed in the bone, implant and abutment region in the large diameter model, while the lowest stress value was recorded in the small diameter model [28]. The results of these FEA studies are, in general, consistent with our findings.

In this FEA study investigating the biomechanical effect of implants placed at different angles in the All-on-four technique, the anatomical structure consisting of mandible, implant, abutment, mucosa and prosthesis was modelled in a one-to-one manner to resemble the clinic, masticatory muscle forces were included in the analysis boundary condition, and it is the first study to be solved by the nonlinear method.

Generally, in FE analyses, linear solution is made by simplifying the boundary conditions in order to solve the problem more easily. This can occasionally result in erroneous outcomes and incorrect solutions in the analysis of problems involving hard (bone) or soft tissue. This can cause the result to drift away from the correct solution. A significant portion of the problems encountered in real life are nonlinear. There is a non-linear relationship between the applied forces and displacements and the solution is considered more accurate in non-linear analysis [4–6,8,9,29]. Three non-linear effects (geometrical nonlinearity; i.e. large deformations, contact and material nonlinearity's.) are taken into account in our study.

In FEA studies, the reliability of the results and the reproducibility and comparability of the analyses are very important. It is necessary and important to define the boundary conditions (type of contact, applied forces, amount of displacement), material properties, mesh structure (number of elements and nodes) and mesh convergence. Especially in the FEA method, the mesh structure of the model has a direct impact on the accuracy of the solution. In the FEA method, it is

undesirable for the analysis result to change depending on the mesh element size change. According to the mesh metrics spectrum value generated by the ANSYS program, mesh convergence should be performed for the reliability of the results (Table 3). Mesh convergence refers to the optimal number of elements that should be present in the model. Thus, depending on the optimum number or size of mesh elements, the analysis solution is not affected. It is not advisable to use low orthogonal quality and high skewness values to obtain accurate and reliable results. The accuracy of the analysis results is influenced by these variables. Accuracy decreases as the mean skewness value increases from excellent to very good to good [4–6,8,9,29].

The study's mesh metrics skewness spectrum value for all scenario models is 0.3. According to the values given in Table 3, the average quality of the mesh convergence of the skew elements for all the components that make up the geometry in our model is of excellent quality.

In the analysis, a very high maximum stress value was measured in the models (multiunit abutment, implant and bone), as shown in the color scale. The maximum measured stress value for the implant and abutment placed at an angle is as follows: Model IV (564 and 782 MPa), Model III (704 and 719 MPa), Model II (484 and 691 MPa) and Model I (296 and 357 MPa), respectively. Upon examination of the maximum stress regions in the analysis (illustrated in red), it becomes evident that the stress is concentrated and accumulated at the nodes and on several elements within that region.

The maximum stress value in the models is caused by sharp angular regions (singularity) which are due to the design and cannot be avoided. In the FEA, the stress values in the singularity regions (i.e., sharp corners and edges) are much higher than the normal value. This is due to calculation (programme) errors in the FE method. In reality, the maximum stress value does not accumulate at a single point, as in the analysis result, due to the ability of the bone to flex and repair itself in the face of applied loads [4–6,8,9,29]Therefore, the maximum stress value in the solution did not affect the results as it is due to the singularity and is a function of the FEA process.

4.1. Limitations

The present study did not consider bone remodelling, soft tissues (such as lips and cheeks) and different masticatory forces (bruxism). Since the response of soft tissue is not known exactly and the facial muscles and bone density values of individuals are different from each other, the analysis results are the values found according to the average material properties obtained in the literature. The clinical situation was tried to be simulated with accurately modelled anatomical structure, boundary conditions and material properties. Due to these limitations, our FEA results may differ from in vivo conditions, stress and displacements values may be higher than clinical values.

5. Conclusions

In the information of the results and the information obtained in this FEA study, it can be reached to derive certain surgical implications for the All-on-four treatment.

Among the models, the lowest von Mises stress value on the implant and abutment was measured in model-I and the highest in model-IV. Implants and abutments placed in the distal region showed the highest stress values.

Biomechanical stress value on implant and abutment increases as the inclination or angle of implant insertion into the bone increases. The Von Mises stress value is concentrated in the neck region where the implant and abutment are connected to each other in all scenario models.

Within the limitations of FEA modelling, it is possible to achieve biomechanical and clinical advantages in patients undergoing edentulous mandibular rehabilitation with the All-on-four technique using implants placed at neck angled implants or at specific angles.

According to the results of the study, Model-I and Model-II with low stress values can be recommended for patients with clinical conditions and biomechanical risk factors. Concurrently, the absence of the necessity for supplementary surgical procedures, such as additional bone correction at the surgical stage, may be regarded as an advantage for the neck-angled implant.

Further data (in vivo / in vitro) and long-term clinical studies are needed to confirm the results of the analyses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yildiz Unuvar: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Aylin Calis:** Conceptualization, Investigation, Methodology, Writing – original draft. **Osman Koc:** Software, Visualization, Writing – original draft, Writing – review & editing.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jormas.2024.102157.

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