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Evaluation of biomechanical effects of different implant thread designs and diameters on all-on-four concept

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ABSTRACT

Aim All-on-four concept involves the use of four anterior dental implants in the edentulous jaw to overcome anatomic limitations of residual alveolar bone. The impact of implant thread design and diameter on the biomechanical performance of all-on-four concept is not yet fully understood. The purpose of this study was to investigate the biomechanical behavior of all-on-four concept with different combinations of thread designs and diameters through a three dimensional Finite Element Analysis.

Materials and methods Six three-dimensional finite element models of edentulous mandible were developed. The models included the combinations of 3.5 and 4.3 mm diameter implants with active and passive thread designs. Vertical, oblique and horizontal loads were applied anterior to the end of the cantilever. Von Mises, maximum principal and minimum principal stresses were analysed.

Results The results indicated a tendency towards stress reduction in Von Mises stress values of dental implants with the increase in diameter for both mesial and distal implants. In narrow implants active thread design resulted in lower Von Mises stress values than passive thread design. Active thread design demonstrated higher bone stress when compared to passive thread design. The analysis also revealed the importance of mesial implant for diminishing stresses on the distal implant and their surrounding bone under horizontal and oblique loading.

Conclusion The comparison of the models suggest that use of wide implant is advantageous in the all-on-four concept. There is a biomechanical advantage in using narrow implants with active thread design in horizontally inadequate bone. The thread design was more significant in terms of increasing bone stress than implant diameter. The mesial implant influences the biomechanical behavior of the whole design, contributing to a more favorable stress distribution under horizontal and oblique loading conditions.

KEYWORDS All-on-four, Dental implants, Finite element analysis, Mandible.

INTRODUCTION

Excessive bone resorption of the alveolar ridge is common in edentulous patients. In these patients, dental implant placement may be challenging due to the anatomical structures of the residual alveolar bone such as mandibular canal and maxillary sinuses, often requiring bone augmentation procedures (1). The all-on-four concept was developed to solve these problems and offer less invasive treatment which allows the rehabilitation of a fully edentulous jaw with bone resorption, short treatment intervals, lower treatment cost, lower morbidity and the improved quality of life (2, 3).

The all-on-four concept requires the placement of four anterior implants in an edentulous jaw, with the distal implants being tilted between 30° and 45°. This allows the use of longer implants providing a good primary stability to avoid damage on the mental nerve or inferior alveolar nerve in the mandible, and eliminating the need of maxillary sinus graft, in the maxilla (2, 4). Based on the optimal number of four implants, the concept has the advantage of the posterior tilting of the two distal implants with a maximum of a two-tooth distal cantilever in the final prosthesis (5). The tilting of distal implants minimizes the cantilever extention, thereby resulting in decreased peri-implant bone stress (3).

High survival rates have been demonstrated for all-on-four concept (5-8). Previous biomechanical studies on this concept have also shown favorable reduction of stresses in the bone, framework and implants (9,10). However some biomechanical questions arose concerning the load distribution of the implants (3, 11).

Load distribution of an implant may be affected by implant parameters including implant diameter and thread design (12, 13). Dental implants are in direct contact with the bone, and so changing these parameters can directly affect the transmission of occlusal forces from the implant to the bone, and may change the distributions of stresses in both the implant and the surrounding bone. Higher stresses in the bone around an implant resulting from overloading may increase the risk of damage to the bone or marginal resorption (14). However a few researchers have evaluated the impact of implant thread design and diameter on the biomechanical performance of all-on-four concept (14-16). Therefore the stress analyses of all-on-four design need to focus on these parameters.

It is very difficult to calculate forces in living structures. Furthermore, identifying the response of the tissue is problematic and sometimes impossible. Modelling the living organ and analyzing the biomechanics of the tissue using simulated models is a realistic method. Therefore *in vitro* studies have become important to analyze the biomechanical behaviour of dental implants (17).

Finite Element Analysis (FEA) has been widely used for the evaluation of the effects of stress on the implant and its surrounding bone (12). The FEA is a method to solve a complex problem by subdividing it into a collection of smaller and simpler problems that can be clarified using numerical techniques. The approximate solution to the original problem is determined based on the combined solution from smaller, simpler subproblems (18). The use of FEA in implant biomechanics has many advantages over other methods in simulating the complexity of clinical situations (19).

The aim of the present study was to employ three dimensional (3D) FEA to analyze the influence of thread design and diameter on the stress distribution in dental implants and the surrounding bone of the edentulous mandible when four implants are placed according to the all-on-four concept.

MATERIALS AND METHODS

A 3D model of a totally edentulous mandible was constucted as the basis of the initial mandibular finite element model used in the study. Serial axial sections in every 0.5 mm level of an edentulous mandible were selected from NewTom 3G (Quantitative Radiology, Verona, Italy) Cone-Beam Computed Tomography (CBCT) imaging system. The CBCT images were saved using DICOM 3.0 as a medical image file format and transferred to Maxilim Software (Medicim Company, Mechelen, Belgium) version 2.2.2, as a 3D medical image processing programme. The 3D image of the mandible with the .stl file format was imported into MSC Mentat (MSC Software Corporation, CA, USA) version 2005 for pre-processing and modelling. All the final solid meshes were constituted by tehrahedral elements with four nodes.

Six different finite element models (M1-M6) presenting a 15 mm long distal cantilever were created. The geometry of the implants was simulated according to engineering drawings using MSC Mentat (MSC Software, Santa Ana, CA, USA). Nobel Active (representing active thread design) and Nobel Replace (representing passive thread design) implants with multi-unit abutments were used in order to generate the models and modeled using the manufacturers' data (Nobel Biocare, Zurich, Switzerland). M1-M6 models represented the all-on-four concept with 3.5 or 4.3 mm diameter and 11.5 mm long dental implants in various combinations of active and passive thread designs. The details of the models are shown in Table 1. In each model 4 dental implants were placed in the interforaminal region. Two mesial implants were placed in the lateral incisor region and positioned perpendicular to the occlusal plane. The distal implants were inserted anterior to the mental foramina and were standardly tilted in 30° angle distally relative to the occlusal plane. The general view of all-on-four models is shown in Figure 1.

In the absence of information regarding the precise organic material properties of bone and other materials modeled and used in this study, they were considered to be isotropic, homogenous and linearly elastic. The elastic properties are shown in Table 2 and taken from the literature (20).

As there are no experimental data in the literature for the comparison of our results, a convergence test was performed to verify the model accuracy. The results were assessed using the results of the Von Mises stress values of Model 1 for vertical load with changing number of elements and final numbers of validated elements and nodes (Fig. 2). Changes of < 1% in the Von Mises stresses indicated convergence. The numbers of elements and nodes for the models are shown in Table 3.

A wide range of chewing forces has been mentioned in the literature (21). A ratio of 5:2.5:1 was reported for vertical, buccolingual and mesio-distal loads during chewing (22, 23). Therefore 150 N (Newton) vertical, 75 N oblique and 30 N horizontal loads were applied anterior to the end of the 15 mm long cantilever (24). The models were separately analyzed and compared each other for the vertical, horizontal and oblique loading conditions.

Boundary fixations were set as constraining all three degrees of freedom at each of the nodes located at the most external mesial or distal aspect of the models. A fixed bond between implant and bone was assumed to simulate good osseointegration. The same type of interaction was provided at all material interfaces. The

All-on-four models	Distal implant (R†)	Mesial implant (R)	Mesial implant (L‡)	Mesial implant (L)
M1	3.5 mm active	3.5 mm active	3.5 mm active	3.5 mm active
M2	3.5 mm passive	3.5 mm passive	3.5 mm passive	3.5 mm passive
M3	4.3 mm active	4.3 mm active	4.3 mm active	4.3 mm active
M4	4.3 mm active	3.5 mm active	3.5 mm active	4.3 mm active
M5	3.5 mm passive	4.3 mm passive	4.3 mm passive	3.5 mm passive
M6	4.3 mm active	4.3 mm passive	4.3 mm passive	4.3 mm active

† Right; ‡ Left

TABLE 1 **Design of all-on-four models.**

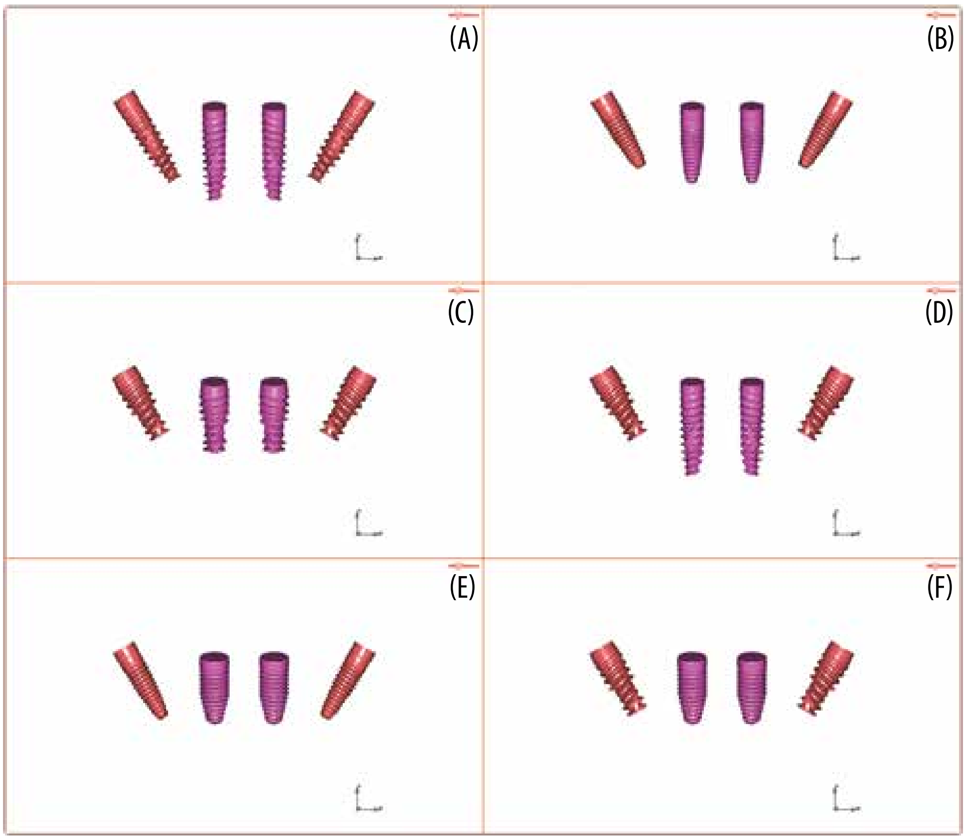

FIG 1
General view of all-on-four models, (A)M1, (B)M2, (C)M3, (D) M4, (E)M5 and (F)M6.

	Young's modulus (E) GPa§	Poisson Ratio ( )
Cortical bone	14.8	0.30
Cancellous bone	1.85	0.30
Titanium	105	0.33

§ *Giga Pascal*

TABLE 2 Mechanical properties of bony structures and dental implant material in finite element analysis

	Elements	Nodes
M1	476933	90813
M2	842178	153504
M3	492522	91942
M4	475798	89806
M5	704057	130342
M6	476669	90893

TABLE 3 Number of elements and nodes for the models.

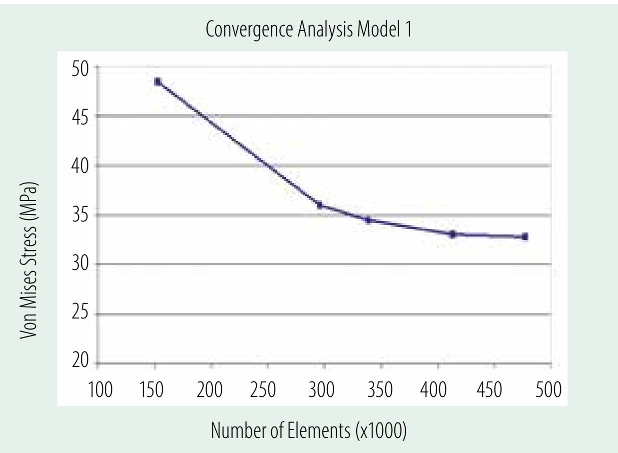

FIG 2 Graphic representation of convergence test results.

MSC MARC 2003 (MSC Corporation, Santa Ana, CA, USA) finite element solver was used to calculate the stresses in each model.

There has been no consensus in the literature regarding the type of stresses that should be used in the analyses. The Von Mises stress values represent the beginning of deformation for ductile materials such as dental implants. Von Mises stress measure is appropriate for analyzing dental implants (25,26). Bone can be described as a brittle material from an engineering point of view and Von Mises stress measure does not allow a distinction between tensile and compressive stresses on bony tissues. Therefore maximum principal (Pmax) and minimum principal (Pmin) stress measures were used to analyze the biomechanical behavior of peri-implant bone (15, 25, 26). With this contex the Von Mises stress values on dental implants, Pmax stresses (tensile stresses) and Pmin stresses (compressive stresses) on peri-implant bone were predicted by means of 3D FEA. All stress values were given in Mega Pascal (MPa)(Newton per milimeter square). The highest values of Von Mises, Pmax and Pmin stresses are shown in Figure 3.

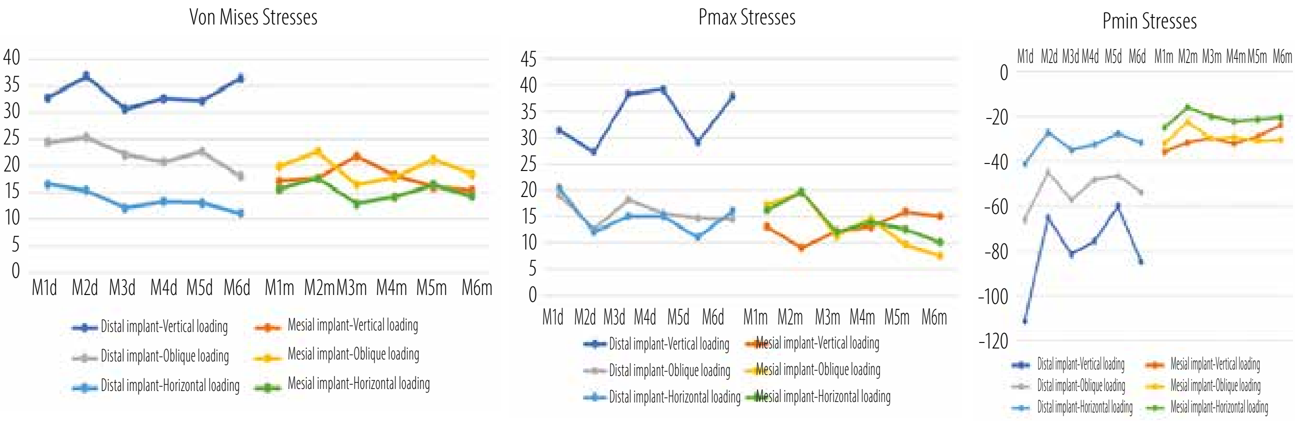

FIG. 3 Highest Von Mises, Pmax and Pmin stress values under different loading conditions, v: vertical; o:oblique; h:horizontal m: mesial, d:distal.

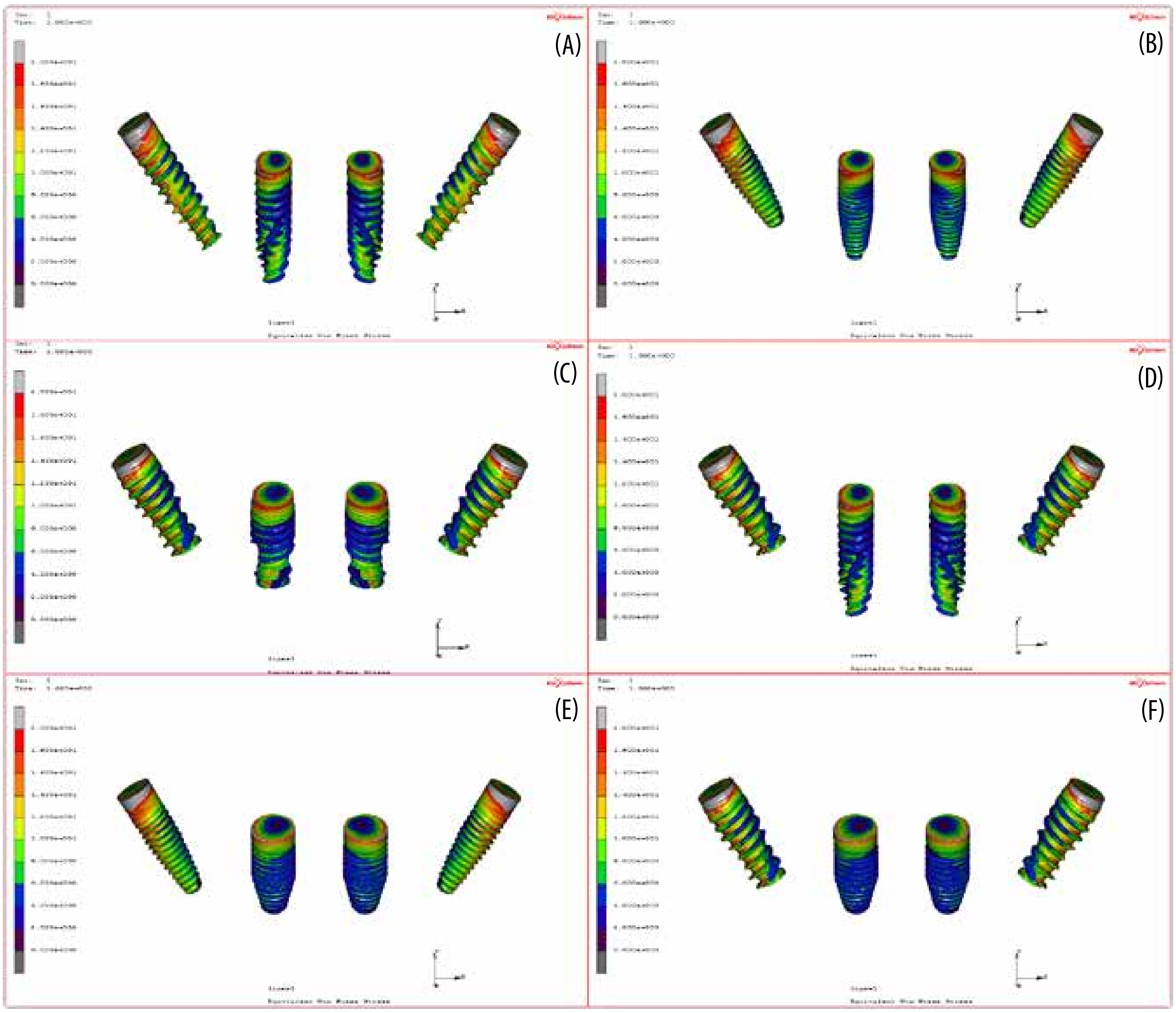

FIG 4 Three dimensional Von Mises stress distribution fields under vertical loading in a)M1, b)M2, c)M3, d)M4, e)M5 and f)M6 models.

RESULTS

Evaluation of Von Mises stress values

Von Mises stress distributions in the implants under vertical loading are illustrated in Figure 4. The highest stresses were recorded under vertical loading condition. The stresses were mainly concentrated at the distal and buccal aspects of the implants. The highest values were

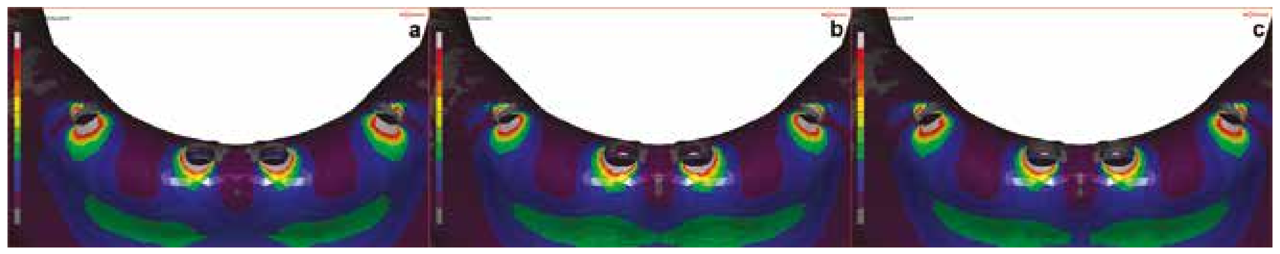

FIG. 5 Three dimensional Pmax stress distribution fields under horizontal loading in a)M4, b)M5 and c)M6 models.

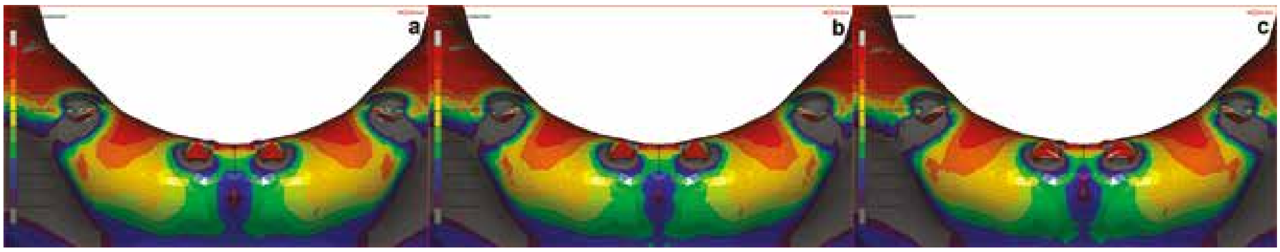

FIG. 6 Three dimensional Pmin stress distribution fields under vertical loading in a)M1, b)M2 and c)M3 models.

mostly noted on the distal implants.
The highest Von Mises stresses for distal implants were measured in M2 model for vertical and oblique loading, and in M1 model for horizontal loading. The lowest stress values for distal implants were detected in M3 model for vertical loading, and in M6 model for oblique and horizontal loading. The highest stresses for mesial implants were seen in M3 model for vertical loading, and in M2 model for oblique and horizontal loading. The lowest values for mesial implants were isolated in M6 model for vertical loading, and M3 model for oblique and horizontal loading.

Evaluation of Pmax stress values

Pmax stress distribution for different models under horizontal loading are shown in Figure 5. The highest stresses were noted under vertical loading. Pmax stresses in the surrounding bone of distal implants were generally greater than the mesial implants. The highest stresses around distal implants were measured in M4 model for vertical loading, and in M1 model for oblique and horizontal loading. The lowest stresses for distal implants were obtained from M2 model for vertical and oblique loading, and from M5 model for horizontal loading. Evaluation of Pmax stress values around mesial implants revealed that the highest stresses were observed in M5 model for vertical loading, whereas M2 models had the highest stress values for oblique and horizontal loading. The lowest stresses in the surrounding bone of mesial implants were found in M2 model for vertical loading, and in M6 model for oblique and horizontal loading.

Evaluation of Pmin stress values

Pmin stresses around dental implants under vertical loading are described in Figure 6. Stresses in the surrounding bone of distal implants were greater than the mesial implants for all models and loading conditions. The highest Pmin stress values were isolated in vertical loading condition. M1 model exhibited the highest stresses for distal implants under all loading conditions. The lowest stresses for distal implants were recorded in M5 model for vertical loading, and in M2 model for oblique and horizontal loading. The highest Pmin stress values around mesial implants were measured in M1 model for all loading conditions. The lowest stress values were seen in M6 model for vertical loading, and in M2 model for oblique and horizontal loading.

DISCUSSION

Malo et al. introduced the all-on-four concept of four implants supporting full-arch fixed prostheses in an edentulous mandible as a viable, simple and cost-effective protocol (27). Several authors have investigated this concept in order to identify the biomechanical factors contributing to its success (10, 28, 29).
Implant diameter and thread design have an impact on the stress distribution of dental implant and peri-implant bone (30-33). However, it is unclear how the combination of these variables impact the biomechanical behavior of dental implants and the surrounding bone in the all-on-four concept. Given the absence of experimental studies in the literature, this study aimed to evaluate the effect of combinations of different implant diameters and thread designs on the biomechanical behavior of all-on-four concept.
The FEA is a useful numerical method to investigate clinical situations that are difficult to standardize during *in vitro* and *in vivo* experiments. The validity of the findings depends on the precision with which the geometry, material properties, interface and loading condition are

in accord with physical reality (34). However, the FEA has some disadvantages. A critical subject is the creation of very complex models. Some simplifications and assumptions are necessary for a possible solution, affecting the final result. Some simplifications and assumptions include simplification of geometric properties of bone or implant system assuming that the bone is homogeneous and isotropic, boundary conditions and of bone-implant interface etc. (35).

In the present study six separate all-on-four models including combinations of different thread designs and diameters were analyzed. The materials were assumed to be 100% homogeneous, isotropic and linear elastic. However FEA represents a simplification of the real structure, therefore our findings should be taken as predictions within the limitations of the models presented.

Tilting the distal implants in the edentulous jaws is an alternative solution, enabling the insertion of longer implants, improvement of prosthetic support with a shorter cantilever arm, improved interimplant distance and anchorage in the bone. However, some studies regarding single implants have demonstrated that tilted implants may cause increased stress values on the implant and the surrounding bone (1). In the present study greater stresses were calculated on the distal implants and their surrounding bone. This is consistent with previous studies, where the highest stresses were observed on distal implants and the surrounding bone in the presence of a distal cantilever (9, 36). The distal implant must resist high compressive forces and bending moments due to a cantilever effect. Therefore the attention should be paid to the distal implant design in the all on four concept.

Wide diameter implants provide a larger area of contact and improve the transfer of occlusal loads to the bone tissue (37). The results showed that lower Von Mises stresses arose on wide implants, whereas greater Von Mises stresses were noted on narrow implants. The lowest Von Mises stresses were recorded in M3 and M6 models. Narrow implants exhibited greater sensitivity to the loading direction than wide implants. The impact of increasing only the mesial or distal implant diameter on the stress values of dental implants and the surrounding bone was also assessed in the present study. An improvement of stress values with using a wide diameter for only mesial or distal implant can be observed with the comparison of M1-M4 and M2-M5 models. This indicates that even placing a wide implant for only mesial or distal implant position is beneficial for reducing Von Mises stress values. Therefore it was concluded that wide diameter was an important factor in the stress distribution of both mesial and distal implants for reducing Von Mises stresses.

Thread design is a critical component in biomechanical optimization of the dental implant. Threads are used to increase initial contact, improve initial stability and increase implant surface area (19). The type of force that is formed depends on the thread design. Hence, an ideal implant thread design should establish a balance between compressive and tensile forces while reducing shear force generation (31).

Thread designs include V-shape, square shape, buttress, reverse buttress shape and spiral (38). Variable thread geometry (active) and reverse buttress thread (passive) designs were modeled and the impact of thread design on the stress distribution of dental implants and the surrounding bone in the all-on-four concept was evaluated in this study.

The variable-thread geometry of the active design has a gradually expanding tapered implant body with a gradually increasing thread width. The implant has two reverse cutting flutes and sharp apical threads. The reverse-cutting action of the threads expands gradually. The coronal portion of the implant has a back taper. The passive design has a tapered implant body with reverse buttress grooves and uniform grooves over the entire implant. The thread steps and lengths are also uniform over the entire implant body. The thread step is shorter than the active design (30).

The results on the effect of different thread designs revealed that the thread design tended to clearly influence Von Mises stress values. The Von Mises stresses have been shown to decrease with active thread design in narrow diameter implants. This result may be due to the increased bone contact of the active design, which may have a positive effect on the stress distribution of dental implant. As bone quality cannot be changed, selection of the appropriate implant design is mandatory in order to improve the magnitude of stress that is transferred to the bone, especially in atrophic ridges (11). Successful clinical outcomes have been reported for the 3.5 mm diameter narrow implants with active thread design placed in atrophic ridges with all-on-four treatment (39). The results of this study showed the biomechanical advantage of active thread design as lower Von Mises stress values were found in 3.5 mm active implants when compared to 3.5 mm passive implants. Our findings predict that for clinical situations with inadequate bone horizontally it is critical to utilize narrow implants with active thread design. While planning such cases, the bone volume should be assessed thoroughly, and the implant design to be used should be more resistant to loads.

The analysis of Pmax stresses have shown that the highest Pmax stresses were calculated in 4.3 mm diameter under vertical loading; and in 3.5 mm diameter for both implants under oblique and horizontal loading conditions. The lowest values have been detected in 3.5 mm diameter for distal implants. Evaluation of the mesial implant demonstrated the lowest stress values in 3.5 mm diameter for vertical loading; and 4.3 mm diameter for oblique and horizontal loading. Moreover active thread design produced higher stresses than passive design. The transmission of bone stresses was thought to be affected by the thread design. This results may indicate that the effect of thread design is more significant in terms of bone stress than implant diameter in the all-on-four concept.

In general, compressive stress (Pmin) is more substantial than tensile (Pmax) stresses and provides reliable information for analyzing bone resorption (38). Reducing the extent of compressive forces and optimizing the stress distribution are vital for increasing long-term success of restorations (16). In the present study Pmin stresses were higher than Pmax stresses in all models, indicating that the bone stresses were mainly in compression. Pmin stresses had the highest values in 3.5 mm diameter implants. Moreover active thread design seemed to increase the Pmin stress values. Given the fact that compressive stress is a determinant for a possible overload of bone tissues, the treatment plan should focus on the ideal dental implant designs and combinations reducing compressive stress values.

The changes in implant geometry resulted in different stress values in the surrounding bone in the present study. Greater bone stresses were recorded in active design. This finding is in contrast with Dündar et al. (30), reporting less accumulation of bone stresses for active design with the same dental implant system. However the authors evaluated bony stresses on a single implant. Moreover the loading conditions were not identical. The difference of the findings may be explained by the different prosthetic designs, as the present study aims to investigate the biomechanical behavior of the all-on-four concept.

The combinations of different implant thread designs for wide implants were also evaluated (M6 model). This combination resulted in reduction of Von Mises stress values in comparison with narrow diameter implants. However increases in the stress values were also detected for the mesial or distal implants. Similar with Von Mises stresses, bone stresses were also increased. Therefore the combination of different thread designs was not found to be effective for the stress distribution in the all-on-four concept.

Several researchers have displayed results for distal implants (1, 3, 15, 29). Nevertheless, the influence of mesial implants on the mechanical aspect of the all-on-four concept is limited in the literature (28). This study analyzed the role of mesial implant in terms of biomechanical behavior of all-on-four concept. When all loading conditions are evaluated, mesial implants were subjected to lower Von Mises stresses in vertical loading, whereas higher stresses were observed in oblique and horizontal loading. This finding was also noted in Pmax and Pmin stresses. While distal implant is critical under vertical forces, the supportive effect of mesial implant is remarkable under oblique and horizontal forces. Therefore it might be concluded that mesial implant is also an important factor for diminishing stresses inthe all-on-four concept. The optimal positioning of the mesial implant with the widest possible diameter may produce a favorable stress distribution. Thus the biomechanical strength of all-on-four concept may be increased and long-term survival rate of distal implants could be improved.

Favorable conditions that keep the force within the physiologic limit of the supporting tissues are related with prosthetic designs. Stress transmitted from implants to surrounding bones depends on the prosthesis type as well as the load direction, the bone-implant interface and implant size. Moreover, stress not only is influenced by implant surface treatment and shape and the surrounding bone, but also by the prosthesis type (28). The way the load is transferred from the all-on-four concept to the bone is complex and four implants are not submitted to the same actions (40). The tilted implants are part of this prosthesis. Therefore the placement of the implants and rigidity of the prosthesis will change the nature of the bending forces (1). The results of this study would have shown differences in case of different implants systems. In addition, the effect of anatomical variations of the bone stuctures, different material properties and applied masticatory forces on the biomechanical behavior of such designs should be thoroughly evaluated.

Unlike previous studies, the authors investigated the combined effects of thread design and diameter on the biomechanical behaviour of the all-on-four concept. The results show that these two factors are related with the stress distibution on the dental implants and the surrounding bone. While this study provides several significant points in terms of biomechanics, the results are limited by the assumptions about the properties of materials and simplifications in the finite element models. In addition static loads were applied to the models, and the implants were considered 100% osseointegrated, which may not represent the real clinical situation. However the results of the numerical studies may provide valuable comparative data on the biomechanical behavior of the prosthetic designs, which may contribute to the treatment planning with dental implants. Prospective clinical studies are required to further evaluate the results.

CONCLUSIONS

Based on the result of this FEA study, the following could be concluded regarding the effects of thread design and diameter of dental implants in the all-on-four concept.

1. The diameter of both mesial and distal implants is an important factor and can diminish stresses when wide implants are used in comparison with narrow ones.
2. Thread design had a significant effect on the stress distribution of the surrounding bone. Active thread design had resulted in higher bone stresses when compared to passive design. The thread design is more relevant to increasing the bone stresses than the implant diameter.
3. Mesial implant plays an important role in reducing stress values of the whole design under horizontal and oblique loading conditions.

Author contributions

This study was presented as an oral presentation at the 24th International Scientific Congress of the Turkish Association of Oral and Maxillofacial Surgery, held on May 23-27 2017, in Muğla (Turkey).

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Formal Analysis: Erkan Erkmen, Ahmet Kurt.
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Methodology: Erkan Erkmen, Ahmet Kurt.
Project Administration: Erkan Erkmen, Ahmet Kurt.
Writing – Original Draft: Zeynep Fatma Zor, Yeliz Kılınç, Erkan Erkmen, Ahmet Kurt; Writing – Review & Editing: Zeynep Fatma Zor, Yeliz Kılınç, Erkan Erkmen.
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Conflict of Interest

The authors declare that they have no conflict of interest.

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