Effects of Occlusal Scheme on All-on-Four Abutments, Screws, and Prostheses: A Three-Dimensional Finite Element Study

Nurullah Türker, DDS, PhD*
Hümeyra Tercanlı Alkiş, DDS, PhD
Steven J. Sadowsky, DDS, PhD
Ulviye Şebnem Büyükkaplan, DDS, PhD

An ideal occlusal scheme plays an important role in a good prognosis of All-on-Four applications, as it does for other implant therapies, because of the potential impact of occlusal loads on implant prosthetic components. The aim of the present 3D finite element analysis (FEA) study was to investigate the stresses on abutments, screws, and prostheses that are generated by occlusal loads via different occlusal schemes in the All-on-Four concept. 3D models of the maxilla, mandible, implants, implant substructures, and prostheses were designed according to the All-on-Four concept. Forces were applied from the occlusal contact points formed in maximum intercuspation and eccentric movements in canine guidance occlusion (CGO), group function occlusion (GFO), and lingualized occlusion (LO). The von Mises stress values for abutment and screws and deformation values for prostheses were obtained, and results were evaluated comparatively. It was observed that the stresses on screws and abutments were more evenly distributed in GFO. Maximum deformation values for prosthesis were observed in the CFO model for lateral movement both in the maxilla and mandible. Within the limits of the present study, GFO may be suggested to reduce stresses on screws, abutments, and prostheses in the All-on-Four concept.

Key Words: All-on-Four concept, implant, occlusion, finite element analysis

INTRODUCTION

Because of the superior properties of implant applications in achieving aesthetic and functional needs, there has been a burgeoning demand. However, various biological and mechanical problems may arise in implant-supported prostheses.[1–3] Although there persists a controversy in the role implant loading plays in peri-implant disease, prosthetic complications have been related to nonoptimal occlusal designs.[4] Hyperloading during functioning may cause mechanical complications in the abutments, screws, and prostheses.[1,3] These complications can be minimized by providing an ideal occlusion that is designed with a sufficient number of implants. However, the type of occlusion to be used in treatment with implants is still not established in the literature.[5–7]

Factors such as deficiencies in bone tissue, the presence of patients in whom complex surgical procedures cannot be performed, the obstacles caused by anatomical formations, and economic reasons have directed clinicians to seek methods performing full-arch fixed prosthetic restorations with fewer implants. In this respect, the basis of the treatments in which complete arch fixed prosthetic restorations were performed with 4 implants was foreshadowed by Branemark.[8] Implant tilting suitable for the remaining bone anatomy has been documented by Mattson et al[9] and Krekmanov et al.[10] Malo et al[11,12] introduced the popular concept called "All-on-Four" that allows immediate function with a complete arch implant-supported fixed prosthetic treatment. In this concept, the implants in the posterior region are placed with an inclination into the distal side of up to 45 degrees. This angle in the posterior region allows the placement of the implant by avoiding anatomical formations such as the maxillary sinus and the mandibular nerve. Thus, the surgical procedure becomes safer and more economical.[11,12]

In the All-on-Four concept, fixed prosthetic treatment is performed with fewer implants compared with other concepts. Intraoral occlusal loads are transferred to the implants by using fewer abutments and screws, underscoring the importance of distributing occlusal stress equitably in the implant prosthetic design. In All-on-Four treatments, it is studied which occlusal scheme is more ideal in terms of the distribution of stresses that will occur in bone tissue.[13] However, there is not any information about which type of occlusion is preferred in the All-on-Four concept to create more ideal stresses in abutments, screws, and prostheses.[5,7] Thus, the aim of this finite element analysis (FEA) study is the investigation of the different stress distributions on abutments, screws, and prostheses generated by various occlusal schemes, in accordance with the All-on-Four technique on both arches.

Department of Prosthodontics, Akdeniz University Faculty of Dentistry, Antalya, Turkey.
* *Corresponding author,* e-mail: nurullahturker@hotmail.com
https://doi.org/10.1563/aaid-joi-D-19-00334

MATERIALS AND METHODS

Three separate models were prepared within the scope of the study: CGO, a model in which the occlusal scheme is prepared according to canine-guided occlusion; GFO, a model in which the occlusal scheme is prepared according to group function occlusion; LO, a model in which the occlusal scheme is prepared according to lingualized occlusion.

The methodology of the present study was reviewed by an independent statistician.

Obtaining the models

Modeling of the Bone and the Gingival Tissues

The modeling of the maxilla and mandible was performed using a head and neck anatomy book as a reference.[14] After these structures were modeled, trabecular bone, cortical bone (thickness of 2 mm), and gingiva (thickness of 1 mm) were formed via the "shell" and "subtract" commands.

Modeling of the Prosthetic Restoration

To represent the maxilla and mandible alveolar crest, a standard plaster model was used. Tooth setting for prosthetic restorations to be created in different occlusal schemes was performed on these models. Wax occlusal rims were prepared on the registration bases, adapted, and polymerized to the plaster model. In all 3 types of occlusion, the interarch distance was set to 30 mm, and the occlusion plane was positioned in the middle of the maxillary and mandibular crest. The closure relationship between the models was provided to be standard on all 3 models, and the models were thus mounted on a semiadjustable articulator (Stratos 200, Ivoclar Vivadent, Schaan, Liechtenstein). Although anatomical artificial teeth were used for CGO and GFO, anatomical teeth in the maxillar prosthesis and modified nonanatomic teeth (Ivostar, Ivoclar Vivadent) in the mandibular prosthesis were used for LO. The second molars were not included. Cuspal contacts and eccentric relationships were provided in accordance with the standards of each occlusion type. Three-dimensional images of prostheses separated from plaster models were obtained using a scanning device (D250, 3Shape). Then, the point cloud models of the scanned prostheses were arranged using the Autodesk meshmixer software (Autodesk Inc) and transferred into the Space Claim software (Version 14.5.7, ANSYS Inc), which is a module of the Ansys software. The base sections of the prostheses were made exactly the same using this software and adapted into the mandible and maxilla. The dimensions of the maxillary prosthesis in the frontal direction and the sagittal direction were 41 and 56 mm, respectively, whereas in the mandibular prosthesis, these sizes were 39 and 51 mm. Although it varies by region, the average thickness of the maxillary prosthesis was approximately 16 mm and the thickness of the mandibular prosthesis was 15 mm.

Modeling the Implant and Implant Parts

Root-shaped implants were designed with sizes of 4 × 13 mm for the posterior regions and 4 × 10 mm for the anterior regions (OsseoSpeedtx 4.0 S, Astra Tech). In accordance with these implants, linear abutments (20° UniAbutment 3.5/4.0, Astra Tech) for the anterior regions and angular abutments (Angled Abutment 3.5/4.0, Astra Tech) for the posterior regions were designed. The designs were produced in actual sizes with reference to the demonstration models of the relevant company. The implants, abutments, screws, and prostheses designed were located within the bone tissue model in accordance with the All-on-Four concept. The distal inclination of the implants in the posterior region, which is characteristic for the All-on-Four concept, was adjusted to be 40 degrees both in the maxilla and mandible. The distance between the 2 anterior implants in the maxilla was 30.8 mm, and the distance between the posterior implant and the anterior implant was 31 mm. The distance between the 2 anterior implants in the mandible was 28.4 mm, and the distance between the posterior implant and the anterior implant was 30.2 mm. The bars were designed with a width of 5 mm and a height of 3 mm to cover the entire arch; the abutments were set in the buccolingual center of the bar. The length of the bar was 95 mm in the maxilla and 94 mm in the mandible. The cantilever extension was 6.3 mm in the maxillary prostheses and 7.1 mm in the mandibular prostheses. All these designs were performed in the Space Claim module of the Ansys software. Figure 1 shows the designed maxilla and mandible, implants, abutments, screws, and prostheses.

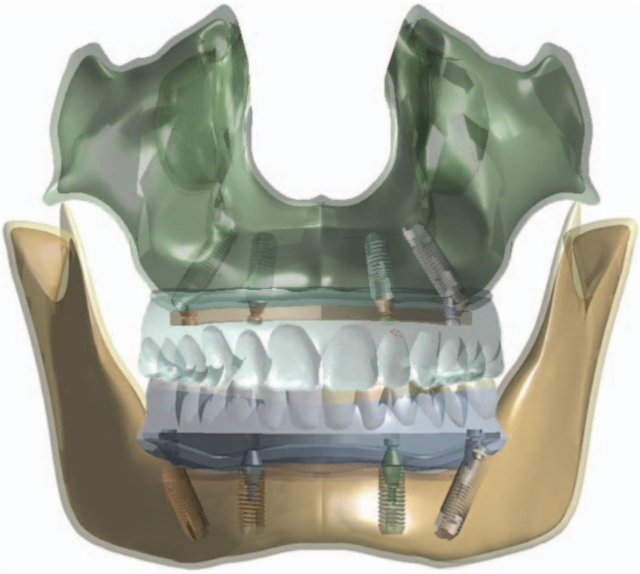

FIGURE 1. Maxillary and mandibular models with completed design and assembly.

Describing the meshing process and the material characteristics

SOLID187 tetrahedral elements were used to compose the mesh. In the present study, the number of total elements was 1,250,334 for the maxilla and 1,517,477 for the mandible (Figure 2). Elasticity modulus and Poisson's ratio values of the materials were identified as in Table 1. Physical properties of type 3 bone were preferred for trabecular bone.[15] All the models were accepted as linear elastic, 100% homogenous, isotropic, and completely bonded.[16,17]

Figure 2. A cross section from the model to which the mesh process is applied.

Determining the boundary and loading conditions

The models were fixed by considering some muscle anchor points in the mandible and bone junction points in the maxilla. The loading conditions were formed with regard to the maximum intercuspation and the forces in eccentric movements in 3 different types of occlusion. The forces were directed through the tubercle contact points formed on each occlusion type and perpendicular to the surface where they were applied. The load applied to each tooth was equally distributed to the occlusal contact points of the tooth. The applied force values were consistent with the literature and listed as follows[13,18–23]:

CGO: 450 N in the centric relation, 93 N in the lateral movement, and 94 N in the protrusive movement.
GFO: 450 N in the centric relation, 200 N in the lateral movement, and 94 N in the protrusive movement.
LO: 450 N in the centric relation, 400 N in the lateral movement, and 400 N in the protrusive movement.

Analyses and outputs

Equivalent (von Mises) stress values were obtained from the screws and abutments. Total deformation amounts of the prostheses were recorded. For the standardization of the images according to the prosthetic deformation amounts, the upper limit was 0.14 mm for the mandible and 0.2 mm for the maxilla in the color-deformation bar. The results are compared in Tables 2 and 3 and Figure 3.

RESULTS

Stresses were recorded in megapascals (MPa). The right side was the rotating side in the lateral movement and the left side was the nonrotating side. Although different amounts of stress formed on the right and left sides of the maxilla and mandible in lateral movement, equal stresses occurred on the left and right sides in maximum intercuspation and protrusive movement. Therefore, only the values of the right side for maximum intercuspation and protrusive movement were written in the table. The stresses observed on the screws and abutments in the mandible were generally higher than the maxilla. Tables 2 and 3 show the stresses observed in the screws and abutments and the total deformation amounts observed in the prostheses, respectively.

When Table 2 is evaluated considering all values, the maximum stress values in the screws and abutments were observed in the GFO model in the lateral movement of the maxilla. In the mandible, the maximum values observed in the screws were equal in the CGO and GFO models in protrusive movement; however, maximum values were observed in the abutments of the LO model in lateral movement.

When the stresses on the screws and abutments were examined at maximum intercuspation, the maximum values for the maxilla and mandible were observed in the LO model. The stress amounts were greater in the posterior regions compared to the anterior regions.

When the stresses on the screws were evaluated in lateral movement, the maximum stresses were observed in the CGO model for the maxilla and in the LO model for the mandible. Again, in lateral movement, the maximum stresses on the screws were observed in the right anterior region of the maxilla and in the left posterior region of the mandible. In the abutments, the maximum stresses in the lateral movement were observed in the GFO model in the maxilla and in the LO model in the mandible. Generally, higher stresses were observed on the rotating side in lateral movement.

When the stresses on the screws were evaluated in the protrusive movement, maximum stresses were observed in the

Table 1

Material properties used in the finite element model

Component	Material	Elastic Modulus (GPa)	Poisson Ratio	References
Cortical bone	—	13.70	0.30	13
Trabecular bone	—	1.37	0.30	13
Gingiva	—	0.0028	0.40	14
Base and teeth	Acrylic	8.30	0.28	14
Implants, components, and bar	Titanium	115.00	0.35	13

TABLE 2

Equivalent (von Mises) stresses observed in the screws and abutments*

Jaw, Component and Occlusal Scheme	Maximum Intercuspation		Lateral Movement				Protrusive Movement	
	RP	RA	RP	RA	LA	LP	RP	RA
Maxilla								
Screw								
CGO	32.4	7.1	40.5	95.1	25.5	16.1	14.3	27.1
GFO	32.4	7.1	79.5	56.9	18	6.4	14.3	27.1
LO	34.8	18.2	37.8	14.6	23	63.9	21.15	10.3
Abutment								
CGO	99.7	27	192.6	219.3	83.2	62.9	28.3	113.9
GFO	99.7	27	260.1	197.9	72	32.7	28.3	113.9
LO	129.1	63.7	119.9	53.9	96.8	244.1	104.4	45.7
Mandible								
Screw								
CGO	56.7	28.8	76.7	90.6	62.8	98.8	31.8	131.4
GFO	56.7	28.8	72.9	62.3	22.9	16.7	31.8	131.4
LO	72.9	46.8	66.2	54.5	116.9	60	68	32.7
Abutment								
CGO	140.3	62.3	122.1	123	52.9	50.1	56.7	150.7
GFO	140.3	62.3	195.2	138.3	30.7	27.3	56.7	150.7
LO	151.7	90.4	213.8	199.3	135.4	166.2	144.9	136.5

*LA indicates left anterior; LP, left posterior; RA, right anterior; RP, right posterior; CGO, canine guidance occlusion; GFO, group function occlusion; LO, lingualized occlusion.

LO model in the maxilla and in the CGO and GFO models in the mandible. In the abutments, the maximum stresses were equal in the CGO and GFO models for both the maxilla and mandible. The changes observed in the stress values were similar in the maxillary and mandibular models. However, maximum stress values in lateral movement in the abutments were observed in the GFO model in the maxilla and in the LO model in the mandible.

When the deformation values in Table 3 were considered, the maximum deformation values were observed in the CGO model in lateral movement both in the maxilla and mandible. The lowest deformation values were equally observed in the CGO and GFO models in maximum intercuspation.

DISCUSSION

FEA, has been used extensively in dental research in recent years. It is a useful tool in the examination of stresses occurring

TABLE 3

Total deformations observed in prosthetic structure (mm)*

Jaw, Component and Occlusal Scheme	Maximum Intercuspation	Lateral Movement	Protrusive Movement
Maxilla			
CGO	0.02	0.15	0.04
GFO	0.02	0.09	0.04
LO	0.04	0.07	0.03
Mandible			
CGO	0.14	0.16	0.15
GFO	0.14	0.12	0.15
LO	0.15	0.14	0.13

*CGO indicates canine guidance occlusion; GFO, group function occlusion; LO, lingualized occlusion.

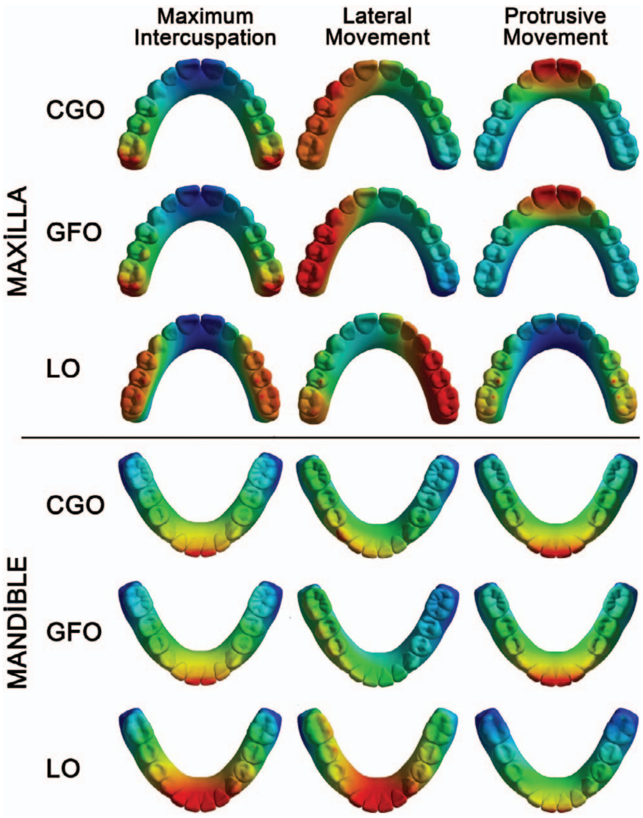

FIGURE 3. Distribution of the deformations occurring in the maxillary and mandibular prostheses. Red shows the regions with maximum deformation, and blue shows the regions with minimum deformation. CGO indicates canine guidance occlusion; GFO, group function occlusion; LO, lingualized occlusion.

in the peri-implant bone, which otherwise would be clinically difficult to detect.[24,25] In this method, the three-dimensional design of the clinical situation is made. Then, the effect of the desired factors is observed by considering all the other factors as standard. In this aspect, this method is advantageous compared with the standardization difficulties of clinical trials. With detailed comparison and interpretation of visual and numerical data obtained through FEA studies, valuable information about complex clinical situations can be obtained.[26]

In the present study, the stresses on the screws and abutments in the mandible were generally higher compared with the maxilla. When this difference was taken into consideration, it could be inferred that the mechanical complications in the maxilla and mandible occurred from different processes. One of the issues to be considered here is the FEA model. The more realistic imitation of the clinical situation provides the more accurate results in FEA studies. Ideally, although modeling the maxilla and mandible, changes in bone tissue in each axial dimension should be reflected in the model. Although various methods have been reported for this type of modeling, these methods have not been adequately tested and have not been proven to provide accurate findings.[27,28] A changed jaw bone structure by regions may cause alterations in the distribution of stresses. However, the main study subject of the present study was to investigate the stress distribution caused by different occlusal schemes on the same bone and implant structure. The main variable in the study is the type of occlusion and the comparison of target occlusion types. In the case of comparison in the finite element analysis, a comparison can be made between independent variables by providing similarity among the models. There are many similar studies conducted in the literature.[23,29] Nevertheless, bone tissue can be modeled more realistically in further studies. However, differences in findings in the maxilla and mandible may be associated with the differences in interimplant distance, cantilever lengths, and anterior/posterior span of the mandible and maxilla. Several authors have reported more mechanical problems in full-arch implant-supported maxillary resin prostheses compared with those in the mandible.[30–33] However, the findings in these studies were obtained from a large data set including fixed prostheses supported by 5, 6, and or 8 implants and the cases where the opposite arch can be composed of natural teeth. In the present study, only the cases where both maxillary and mandibular prostheses were prepared with the All-on-Four concept, and ideal occlusal relations were examined. In addition, cantilevers of the prostheses prepared with the All-on-Four concept are mostly positioned in the area of the first molar teeth, which is the center of chewing. In the models prepared in this study, the cantilever length in the mandibular prosthesis is longer. This may also explain the discrepancy in the results.

When the stresses occurring in the screws and abutments were considered in maximum intercuspation, higher stresses occurred in LO. In CGO and GFO, the forces were applied at the tubercle contact points and divided into more parts than LO. In LO, the loads were distributed from a single point to the prosthesis for each tooth. The formation of higher stresses in LO could be attributed to this force distribution state.

In lateral movement, the stresses on the screws and abutments did not show similar distributions for the maxilla and mandible. The maximum stress value in the maxilla was observed in the anterior screw on the working side in CGO, whereas the maximum value in the mandible was observed in the anterior region on the nonrotating side in LO. The main reasons for this difference observed in standardized models may be differences in tubercle contacts, masticatory forces in lateral movement, and anatomy of the bony structures of the maxilla and mandible. It is worth noting that relatively high-stress values were observed in CGO, although less force was applied compared with the other 2 types of occlusion. The chewing forces are transmitted to the prosthetic parts through the tubercle contact points. The forces transmitted cyclically throughout the chewing processes cause periodically stress in rigidly interconnected fixed prosthetic components. The presence of cyclic stresses accelerates the fatigue in the material structure.[34] This situation may lead to the occurrence of mechanical complications in prosthetic structures in the long term.[35–37] In this context, this may mean that screw loosening and fractures in screws and abutments are more likely to be observed in All-on-Four restorations applying CGO. Forces were distributed more equitably among teeth in GFO, Thus, GFO seems to have advantages for maintaining the stability of the screws and abutments. This was demonstrated as well with lower prosthetic deformations with GFO in lateral and protrusive movements.

In the present study, bar structures were designed similarly to the standard designs used in many studies.[16,23] However, case-specific bars, not standard bars, may be used in an implant-supported prosthetic design. These bar structures usually contain retentive reinforcement in each tooth. Such modifications may reduce the likelihood of mechanical complications,[38,39] and such conditions can cause different results in terms of mechanical problems in different types of occlusion. However, in this study, the effects of occlusion types on stress formation were evaluated by keeping the model designs as standard. This is related to the principle of FEA that comparing some factors by keeping all other features constant. From this point of view, it is thought that the findings obtained in this study do not cover all the implant-supported prosthetic designs in the All-on-Four concept but contribute to the literature in terms of comparison among different occlusal schemes.

Proper treatment planning and proper occlusion prevent overload on the prosthetic parts, and this situation minimizes the incidence of loosening and fracture of the screws.[31] Sakaguchi et al[40] evaluated the biomechanical performance of the restorative components of dental implants via FEA and concluded that uneven loading caused a separation between the crown and the abutment and between the crown and the screw. Alkan et al[41] investigated the stress on the screws in 3 different implant-abutment systems via FEA and showed that the loads coming from different angles caused different stresses.

Based on the results of a review, Abduo et al[42] reported that there was no difference between CGO and GFO in terms of restoration life. Miralles et al[43] stated that both CGO and GFO were equally acceptable for both natural teeth and implant-supported prostheses. Some authors have suggested that LO is more suitable for implant-supported prostheses.[42,44] However, these studies were not limited to All-on-Four prosthetic designs. The results obtained in the present study show that higher stresses occurred in implant-supported components, especially in CGO. Among the 3 occlusion types, lower stress values were generally observed in GFO. However, in a previous study, in the prosthetic restorations produced with 5 different occlusion types in accordance with the All-on-Four concept, the stresses formed on implants and bone tissue were evaluated and the lowest stresses were observed in CGO.[13] Thus, considering the results of both studies, it can be observed that different stress values, and therefore, different findings were obtained for the different parameters examined. Therefore, the result of the 2 studies shows that occlusion types cause different effects on different components (bone, implant, abutment, screw, prosthesis). All-on-Four prosthesis in the low-quality bone may be best served by CGO, and when the bone is not type 3 or 4, GFO may be prudent. Further in vitro and in vivo studies are needed to compare the effects of CGO and GFO in All-on-Four prostheses.

However, when the findings obtained in the study are examined carefully, it is seen that the lowest stresses are observed in GFO after CGO. Thus, considering the results of the both studies may be valuable when establishing an occlusal scheme for all on 4 İmplant concepts. Further in vitro and in vivo studies are needed to compare the effects of CGO and GFO in All-on-Four prostheses.

In the literature, there are contradictory data about the maximum occlusal load that occurs in the implant-supported prosthesis during chewing.[18,45–47] In the present study, the mean values of these data were preferred. The reason for preferring lower force values in the lateral and protrusive movements is that biting forces in excursive positions are less than the value of the biting forces in the centric position.[48–50]

Although it provides benefits in simulating the clinical situation, especially in studies involving comparison, the FEA method also includes several limitations. These are assumptions involving isotropic conditions, material properties, applied boundary conditions, and type of interconnection between structures and the bone/implant interface.[24] In this context, although the results suggested that GFO develops more ideal stresses, this result should be supported by long-term clinical studies, because of the limitations of the FEA method. In the study, the average values of the occlusal loads shown in previous studies were preferred. However, it should be taken into consideration that the values of masticatory force may vary as a result of many factors, such as the age, sex, muscle structure, and parafunctional habits of the individuals.

Conclusions

The following results were achieved within the limits of the present study:

1. When the stresses occurring on the screws and abutments were generally evaluated, the stresses were more ideally distributed in GFO.
2. Higher deformation values were generally observed in CGO in lateral and protrusive movements, which may influence the incidence of mechanical complications in the implant prosthesis over the long term.

Abbreviations

CGO: canine-guided occlusion
FEA: finite element analysis
GFO: group functioned occlusion
LO: lingualized occlusion

Note

The authors declare no conflict of interest.

References

1. Francetti L, Corbella S, Taschieri S, Cavalli N, Del Fabbro M. Medium- and long-term complications in full-arch rehabilitations supported by upright and tilted implants. *Clin Implant Dent Relat Res*. 2015;17:758–764.
2. Schwarz MS. Mechanical complications of dental implants. *Clin Oral Implants Res*. 2000;11:156–158.
3. Storelli S, Scanferla M, Palandrani G, Mosca D, Romeo E. Stratification of prosthetic complications by manufacturer in implant-supported restorations with a 5 years' follow-up: systematic review of the literature. *Minerva Stomatol*. 2017;66:178–191.
4. Misch CE. *Dental Implant Prosthetics-E-Book*. New York, NY: Elsevier Health Sciences; 2014.
5. Kim Y, Oh TJ, Misch CE, Wang HL. Occlusal considerations in implant therapy: clinical guidelines with biomechanical rationale. *Clin Oral Implants Res*. 2005;16:26–35.
6. Koyano K, Esaki D. Occlusion on oral implants: current clinical guidelines. *J Oral Rehab*. 2015;42:153–161.
7. Penarrocha-Diago M, Penarrocha-Diago M, Zaragozí-Alonso R, Soto-Penaloza D, on behalf of the Ticare M. Consensus statements and clinical recommendations on treatment indications, surgical procedures, prosthetic protocols and complications following All-On-4 standard treatment. 9th Mozo-Grau Ticare Conference in Quintanilla, Spain. *J Clin Exper Dent*. 2017;9:e712.
8. Branemark PI, Hansson BO, Adell R, et al. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. *Scand J Plast Reconstr Surg*. 1977;16(suppl):1–132.
9. Mattsson T, Köndell P-Å, Gynther GW, Fredholm U, Bolin A. Implant treatment without bone grafting in severely resorbed edentulous maxillae. *J Oral Maxillofac Surg*. 1999;57:281–287.
10. Krekmanov L. Placement of posterior mandibular and maxillary implants in patients with severe bone deficiency: a clinical report of procedure. *Int J Oral Maxillofac Implants*. 2000;15:722–730.
11. Maló P, Rangert B, Nobre M. "All-on-Four" immediate-function concept with Brånemark System implants for completely edentulous mandibles: a retrospective clinical study. *Clin Implant Dent Relat Res*. 2003; 5:2–9.
12. Maló P, Rangert B, Nobre M. All-on-4 immediate-function concept with Brånemark System® implants for completely edentulous maxillae: a 1-year retrospective clinical study. *Clin Implant Dent Relat Res*. 2005;7:s88–s94.
13. Türker N, Büyükkaplan US, Sadowsky SJ, Özarslan MM. Finite element stress analysis of applied forces to implants and supporting tissues using the "all-on-four" concept with different occlusal schemes. *J Prosthodontics*. 2019;28:185–194.
14. Baker EW, Schünke M, Schulte E, Schumacher U. *Head and Neck Anatomy for Dental Medicine*. New York, NY: Thieme; 2010.
15. Lekholm U, Zarb GA. Patient selection and preparation. In: Branemark PI, Zarb GA, Albrektsson T, eds. *Tissue Integrated Prosthesis: Osseointegration in Clinical Dentistry*. Chicago, IL: Quintessence; 1985:199–208.

16. Almeida EO, Rocha EP, Júnior ACF, et al. Tilted and short implants supporting fixed prosthesis in an atrophic maxilla: a 3D-FEA biomechanical evaluation. *Clin Implant Dent Relat Res*. 2015;17:e332–e342.

17. Özdemir Doğan D, Polat NT, Polat S, Şeker E, Gül EB. Evaluation of "all-on-four" concept and alternative designs with 3d finite element analysis method. *Clin Implant Dent Relat Res*. 2014;16:501–510.

18. Fontijn-Tekamp F, Slagter A, Van Der Bilt A, et al. Biting and chewing in overdentures, full dentures, and natural dentitions. *J Dental Res*. 2000;79:1519–1524.

19. Hidaka O, Iwasaki M, Saito M, Morimoto T. Influence of clenching intensity on bite force balance, occlusal contact area, and average bite pressure. *J Dental Res*. 1999;78:1336–1344.

20. Khuder T, Yunus N, Sulaiman E, et al. Finite element analysis and clinical complications in mandibular implant-overdentures opposing maxillary dentures. *J Mech Behav Biomed Mater*. 2017;75:97–104.

21. Qadeer S, Kerstein R, Kim RJY, Huh J-B, Shin S-W. Relationship between articulation paper mark size and percentage of force measured with computerized occlusal analysis. *J Adv Prosthodontics*. 2012;4:7–12.

22. Roque MA, Gallucci GO, Lee SJ. Occlusal pressure redistribution with single implant restorations. *J Prosthodontics*. 2017;26:275–279.

23. Silva GC, Mendonca JA, Lopes LR, Landre J Jr. Stress patterns on implants in prostheses supported by four or six implants: a three-dimensional finite element analysis. *Int J Oral Maxillofac Implants* 2010;25: 239–246.

24. Geng J-P, Tan KB, Liu G-R. Application of finite element analysis in implant dentistry: a review of the literature. *J Prosthetic Dent*. 2001;85:585–598.

25. Trivedi S. Finite element analysis: a boon to dentistry. *J Oral Biol Craniofac Res*. 2014;4:200–203.

26. DeTolla DH, Andreana S, Patra A, Buhite R, Comella B. The role of the finite element model in dental implants. *J Oral Implantol*. 2000;26:77–81.

27. Aversa R, Petrescu FI, Petrescu RV, Apicella A. Biomimetic finite element analysis bone modeling for customized hybrid biological prostheses development. *Am J Appl Sci*. 2016;13:1060–1067.

28. Chen Y, Dall E, Sales E, et al. Micro-CT based finite element models of cancellous bone predict accurately displacement once the boundary condition is well replicated: a validation study. *J Mech Behav Biomed Mater*. 2017;65:644–651.

29. Sannino G. All-on-4 concept: a 3-dimensional finite element analysis. *J Oral Implantol*. 2015;41:163–171.

30. Davis DM, Packer ME, Watson RM. Maintenance requirements of implant-supported fixed prostheses opposed by implant-supported fixed prostheses, natural teeth, or complete dentures: a 5-year retrospective study. *Int J Prosthodontics*. 2003;16:521–523.

31. Francis L, Zeenath H, Lylajam S, Harshakumar K. Implant screw fracture. *J Dent Implants*. 2013;3:181.

32. Göthberg C, Bergendal T, Magnusson T. Complications after treatment with implant-supported fixed prostheses: a retrospective study. *Int J Prosthodontics* 2003;16:201–207.

33. Jemt T. Failures and complications in 391 consecutively inserted fixed prostheses supported by Brånemark implants in edentulous jaws: a study of treatment from the time of prosthesis placement to the first annual checkup. *Int J Oral Maxillofac Implants* 1991;6:270–276.

34. Fleck N. Fatigue crack growth due to periodic underloads and overloads. *Acta Metallurgica*. 1985;33:1339–1354.

35. de Jesus Tavarez RR, Bonachela WC, Xible AA. Effect of cyclic load on vertical misfit of prefabricated and cast implant single abutment. *J Appl Oral Sci*. 2011;19:16–21.

36. Hanif A, Qureshi S, Sheikh Z, Rashid H. Complications in implant dentistry. *Eur J Dent*. 2017;11:135.

37. Hecker DM, Eckert SE. Cyclic loading of implant-supported prostheses: changes in component fit over time. *J Prosthetic Dent*. 2003; 89:346–351.

38. Bergendal B, Palmqvist S. Laser-welded titanium frameworks for fixed prostheses supported by osseointegrated implants: a 2-year multicenter study report. *Int J Oral Maxillofac Implants*. 1995;10:199–206.

39. Jemt T, Lekholm U. Implant treatment in edentulous maxillae: a 5-year follow-up report on patients with different degrees of jaw resorption *Int J Oral Maxillofac Implants*. 1995;10.

40. Sakaguchi RL, Borgersen SE. Nonlinear finite element contact analysis of dental implant components. *Int J Oral Maxillofac Implants*. 1993;8: 655–661.

41. Alkan I, Sertgöz A, Ekici B. Influence of occlusal forces on stress distribution in preloaded dental implant screws. *J Prosthetic Dent*. 2004;91: 319–325.

42. Abduo JTM. Impact of lateral occlusion schemes: a systematic review. *J Prosthetic Dent*. 2015;114:193–204.

43. Miralles R. Canine-guide occlusion and group function occlusion are equally acceptable when restoring the dentition. *J Evidence Based Dent Pract*. 2016;16:41–43.

44. Hasan MA. Effects of lingualized and linear occlusion schemes on the stress distribution of an implant retained overdenture using finite element analysis. Paper presented at the ASME 2015 International Mechanical Engineering Congress and Exposition; November 13–19, 2015; Houston, Tex. American Society of Mechanical Engineers, 2015.

45. Kaul AGD. Bite force comparison of implant-retained mandibular overdentures with conventional complete dentures: an in vivo study. *Int J Oral Implantol Clin Res*. 2011;2:140–144.

46. Mericske-Stern RHJ, Wedig A, Geering HA. In vivo measurements of maximal occlusal force and minimal pressure threshold on overdentures supported by implants or natural roots: a comparative study, part 1. *Int J Oral Maxillofac Implants*. 1993;8:641–649.

47. Şener İ, Aslan MA, Tek M, Bereket C, Arici S, Shuichi S. The effect of ımplant therapy on maxımum bıte force ın edentulous elderly patıents: an ın vıvo study. *Turkish J Geriatr*. 2015;18:75–80.

48. Shinogaya TBM, Thomsen C, Vilmann A, Matsumoto M. Bite force and occlusal load in healthy young subjects—a methodological study. *Eur J Prosthodont Restor Dent*. 2000;8:11–15.

49. Van Der Bilt ATA, Van Der Glas H, Abbink J. Bite force and electromyograpy during maximum unilateral and bilateral clenching. *Eur J Oral Sci*. 2008;116:217–222.

50. Wıdmalm SE. Maximal bite force with centric and eccentric load. *J Oral Rehabil*. 1982;9:445–450.