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Biomechanical comparison of implantation approaches for the treatment of mandibular total edentulism

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Abstract

Applying four anterior implants placed vertically or tilted in the mandible is considered to provide clinically reasonable results in the treatment of mandibular posterior edentulism. It is also reported that a combination of four anterior and two short posterior implants can be an alternative approach for the rehabilitation of severe atrophy cases. In this study, we aimed to evaluate the biomechanical responses of three different implant placement configurations, which represent the clinical options for the treatment of mandibular edentulism. Three-dimensional models of the mandible, prosthetic bar, dental implant, abutment, and screw were created. Finite element models of the three implant configurations (Protocol 1: Four anterior implants, Protocol 2: Four anterior and two short posterior implants, Protocol 3: Two anterior and two tilted posterior implants: All-on-4™ concept) were generated for 10 patients and analyzed under different loading conditions including chewing, biting, and impact forces. Protocol 2 led to the lowest stress concentrations over the mandible among the three protocols ($p < 0.016$). Protocol 2 resulted in significantly lower stresses than Protocol 3 and Protocol 1 over prosthetic bars under chewing forces ($p < 0.016$). None of the implant placement protocols consistently exhibited the lowest stress distribution over abutments. The lowest stresses over dental implants under the chewing, biting, and impact forces were obtained in Protocol 1, Protocol 2, and Protocol 3, respectively ($p < 0.016$). Protocol 3 was the best option to obtain the lowest stress values over the screws under all types of loading conditions ($p < 0.016$). In conclusion, Protocol 2 was biomechanically more ideal than Protocol 1 and Protocol 3 to manage the posterior edentulism.

Keywords

All-on-4, short implants, finite element analysis, dental implant, edentulous mandible

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Introduction

Dental implant rehabilitation is a predictable treatment method and commonly used for the treatment of edentulism.[1] Rehabilitation of the edentulous mandible by means of implant-supported prostheses was first proposed by Branemark et al.[2] According to the Branemark protocol, at least four dental implants should be used to support a fixed dental prosthesis on the mandible.[3,4] On the other hand, it is necessary to increase the number of implants to reduce stress concentration and provide a homogeneous stress distribution on the underlying bone and implant–prosthesis interface. However, most patients suffer from excessive alveolar bone resorption, which limits the implantation site of the bone tissue. Especially at the posterior mandibular region, resorption of the alveolar bone causes a decrease in height between the inferior alveolar canal, which consists of the inferior alveolar neurovascular bundle, and alveolar crest, complicating the insertion of implants into this region. Several approaches and methods have been described to eliminate this complication[5–7] and one of them is using tilted implants in the interforaminal region to reduce the length of cantilevers and optimize the spread of implants to provide sufficient stability.[5] In this direction, the All-on-4™ concept developed by Maló et al.[6] is one of the most popular

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options to treat mandibular edentulism using angulated implants (All-on-4; Nobel Biocare AB, Göteborg, Sweden). In this concept, four interforaminal implants of which posteriors are tilted distally by 30° are used to reduce the cantilever distance. Thus, more biomechanically efficient distribution of implants can be obtained and cantilever lengths that could be risky for the long-term stability of the distal implants can be minimized.[7] Although some studies reported that bone resorptions and stress concentrations occurred around the inclined implants,[8,9] other studies presented lower stress values in the crestal region of tilted implants.[10]

Although using short cantilevers supported by angulated implants seems useful to treat mandibular posterior edentulism, they cannot restore chewing function adequately.[11,12] In addition, usage of intraforaminal tilted or straight implants to support posterior cantilevered fixed prosthesis may lead to implant failures and prosthodontic complications in the long term.[13,14] Thus, careful treatment planning is critical for cantilever-based treatment approaches like the All-on-4 concept to provide long-term success on the treatment of mandibular posterior edentulism.

Several studies have shown that treatment of posterior edentulism using short dental implant-supported fixed prosthodontics is one of the most reliable treatment procedures to restore normal chewing function on severe atrophy cases.[15–19] Using short implants is less invasive than bone augmentation procedures in the case of insufficient bone tissue.[20,21] Bone augmentation procedures related to some complications such as donor site morbidity, neurosensory disturbances, or graft failures may be eliminated using short dental implants at the atrophied posterior mandibular region.[17,21]

Despite all these studies, it is still not clear which of these different implantation approaches provides ideal biomechanical outcomes in the treatment of mandibular edentulism. Therefore, in this study, we aimed to evaluate the biomechanical responses of three different implant configurations, which represent the clinical options for the intraforaminal dental implant placements in the treatment of mandibular edentulism, using finite element approach under different loading conditions.

Materials and methods

Modeling of the mandibles and dental instruments

In this study, three-dimensional (3D) finite element models of the mandible, prosthetic bar, dental implant, abutment, and screw were generated. The 3D models of the mandibles were created based on the computed tomography (CT) images (SCANORA® 3D, Soredex, WI, USA). CT images (with an axial slice thickness of 0.5 mm) of the mandibles from 10 adult patients suffering from the mandibular total edentulism were acquired from the archive of the Oral and Maxillofacial Surgery Department, Istanbul University, Turkey. All participants provided written informed consent for the use of CT data in the study.

The two-dimensional CT images were converted into 3D models using an image processing software (3D Doctor; Able Software Corp., Lexington, MA, USA). While construction of the mandible models, predefined Hounsfield unit (HU) thresholds for bone structure (lower limit: 226 HU and upper limit: 3071 HU) were defined to distinguish the bone tissues from other body tissues.[22,23]

The 3D models of the dental implant, abutment, and screw, which are made of titanium, and prosthetic bar, which is made of metal-reinforced ceramic, were created using computer-aided design software (SolidWorks, Dassault Systèmes SolidWorks Corp., Waltham, MA, USA) (Figure 1). The prosthetic bar was designed as a solid body (5 mm in height and 5.5 mm in thickness) consistent with the geometry of the mandibles. Dental implants, abutments, and screws were modeled based on the dimensions of Straumann® implant (regular neck implant and standard plus short implant; Straumann Holding AG, Basel, Switzerland), Straumann abutment (cementable abutment and angled abutment), and Straumann compatible single crowns (CSC) occlusal screw (Straumann Holding AG), respectively (Figure 1).

Applied treatment protocols

In the study, the following three implant configurations which represent the clinical options for the treatment of mandibular edentulism were modeled:

1. Configuration I (Protocol 1): Four long straight implants were inserted vertically into the anterior region of the mandible (Figure 2(a)).
2. Configuration II (Protocol 2): Four long straight implants and two short implants were inserted vertically into the anterior region of the mandible and the posterior region of the mandible, respectively (Figure 2(b)).
3. Configuration III, All-on-4 concept (Protocol 3): Two long straight implants and two long distal implants, which were tilted at an angle of 30°, were placed vertically in the anterior region of the mandible (Figure 2(c)).

Finite element analysis

The constructed models were exported to the finite element analysis software (ANSYS Inc., Canonsburg, PA, USA). The models were assumed to have linear elastic, homogeneous, and isotropic characteristics.[24,25] Their mechanical properties were described by Young's modulus and Poisson's ratio. Mechanical properties of the mandible, titanium, abutment, screw, and prosthetic bar are listed in Table 1.[26]

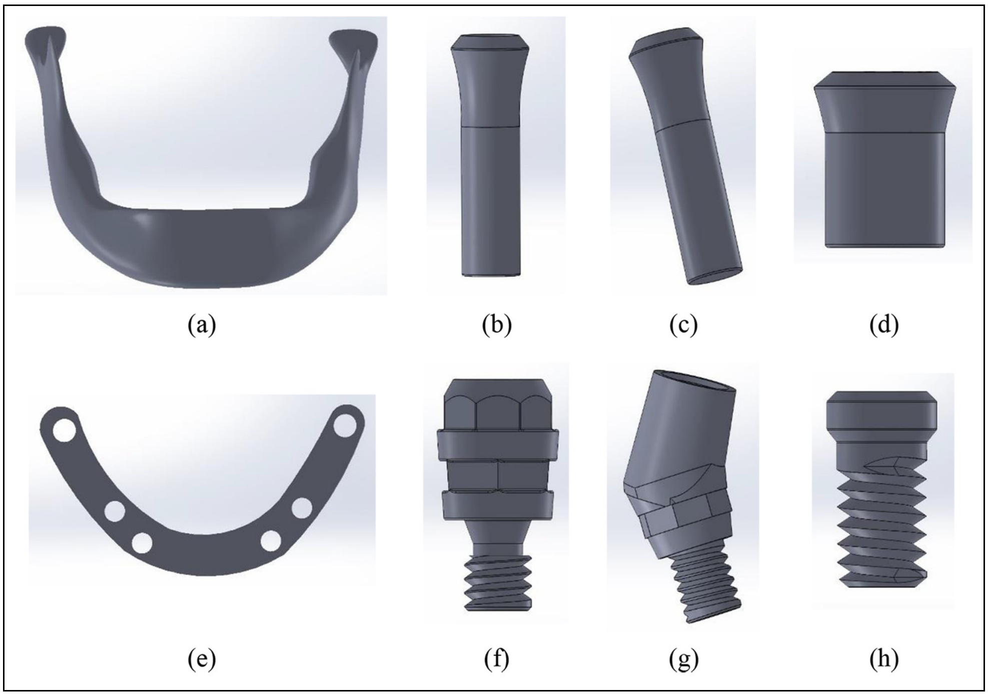

Figure 1. The representation of the geometric models: (a) mandible, (b) Straumann® regular long implant, (c) Straumann regular long implant tilted with the angle of 30°, (d) Straumann standard plus short implant, (e) prosthetic bar, (f) Straumann cementable abutment, (g) Straumann angled abutment, and (h) Straumann compatible single crowns occlusal screw.

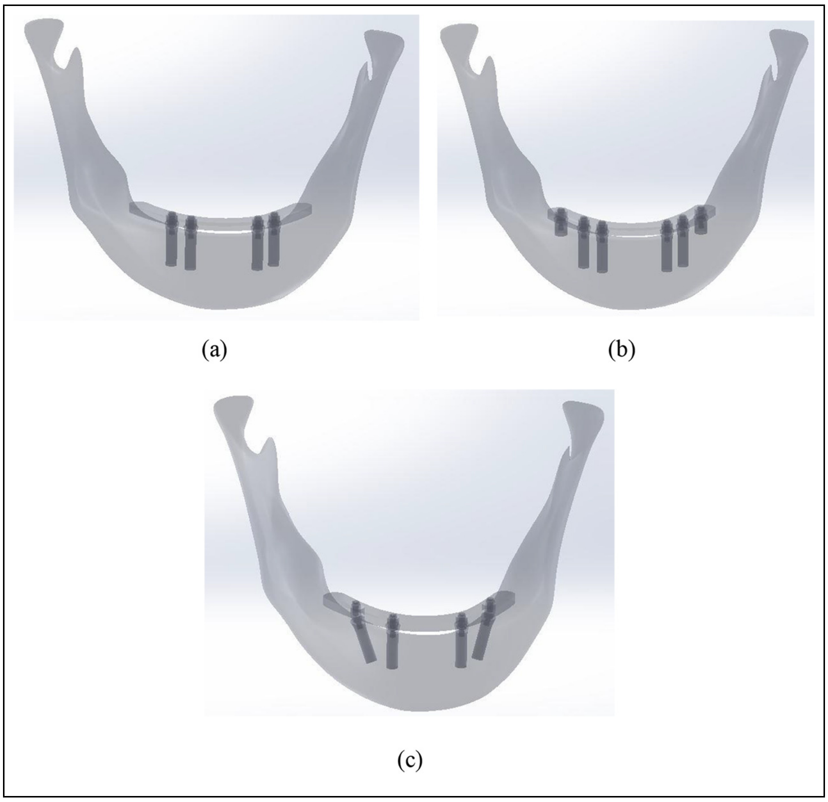

Figure 2. Placement configurations of dental implants: (a) Protocol 1: Four long straight implants were inserted vertically into the anterior region of the mandible; (b) Protocol 2: Four long straight implants and two short implants were inserted vertically into the anterior region of the mandible and the posterior region of the mandible, respectively; and (c) Protocol 3: Two straight long implants and two distal implants, which were tilted at an angle of 30°, were placed vertically in the anterior region of the mandible.

Table 1. Mechanical properties of the mandible, titanium components, and prosthetic bar modeled in the study.

	Young's modulus (GPa)	Poisson's ratio	Yield strength (MPa)
Mandible	15	0.33	130
Titanium implant, abutment, and screw	115	0.33	800
Prosthetic bar	70	0.22	500

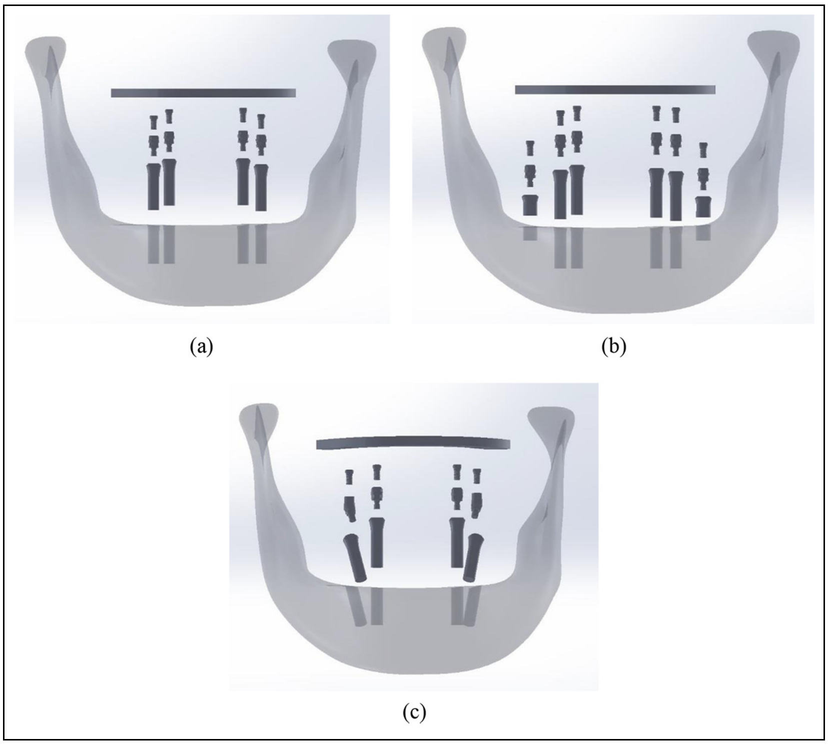

Figure 3. Visualization of the assembly process: (a) Protocol 1, (b) Protocol 2, and (c) Protocol 3.

The implants were fixed firmly to the mandible (Figure 3). Abutment–screw and implant–abutment contacts were also determined as bonded. Boundary conditions of the model were defined according to the temporomandibular joint which was allowed to make only rotational movement. For all cases, loading conditions and analysis were defined as static.

To obtain high computational precision, the tetrahedral element type was selected for the mandible, prosthetic bar, dental implant, abutment, and screw models.[27] According to the mesh convergence tests,[28] 1.7-mm global edge length was specified for the tetrahedral element in the mandible models. For the dental implant, abutment, and screw meshing, 0.3-mm global edge length was chosen. The global edge length of 1 mm was determined for the prosthetic bars, as well. The average number of elements and nodes are as follows: The final mesh structure in Protocol 1 consisted of 260.450 elements and 438.524 nodes, Protocol 2 consisted of 321.875 elements and 557.481 nodes, and Protocol 3 consisted of 279.365 elements and 489.154 nodes.

To evaluate and compare the distribution of stresses on the components of the 10 models, three loading conditions were simulated for each model. For the first loading scenario, a clenching force, which was defined as a vertical load acting upon the surface of the prosthetic bar with a value of 62.8 N,[26] was applied (Figure 4(a)). In the second case, a biting force of 62.8 N[29] was exerted vertically on the anterior region of the mandible (Figure 4(b)). To simulate the last loading condition, a 62.8 N impact force[30] was applied at a 45° angle to the anterior region of the mandible (Figure 4(c)).

In the study, von Mises stress values were calculated for analyzing the stress distribution over the materials. The analyses of principal stresses in the components were performed through graphical visualization of the color maps.

Data analysis

To quantitatively evaluate the stress values, the mean and standard deviation of the maximum stresses occurred over each mandible and dental instrument

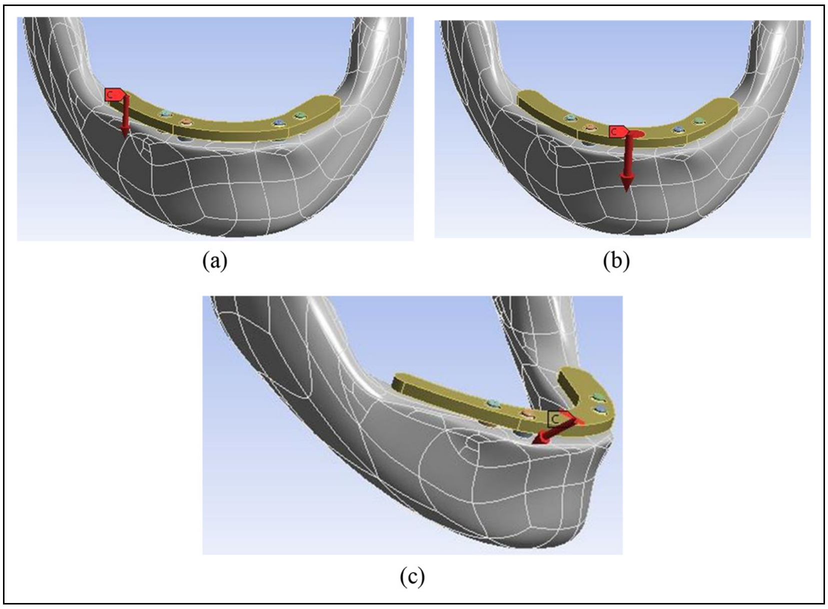

Figure 4. Loading conditions: (a) chewing force, (b) biting force, and (c) impact force. The magnitude of all forces is 62.8 N.

were calculated for Protocol 1, Protocol 2, and Protocol 3. Statistical analyses were performed using the IBM SPSS version 22.0 (IBM Corp., Armonk, NY, USA). The statistical significance threshold was 0.05. Shapiro–Wilk test was performed to examine the normalization of the data. A one-way analysis of variance (ANOVA) test was used to determine the statistical differences between the groups if any ($p < 0.05$). Tukey post hoc test was implemented to reveal the statistical difference between paired groups with a level of significance of 0.016.

Results

To be able to observe the locations of the stress concentrations over the materials, representative von Mises stress distributions over the mandible, dental implant, abutment, screw, and prosthetic bar under chewing, biting, and impact forces are shown in Figure 5. It can be deduced from the figures that all stress concentrations over the mandible under three different loading conditions occurred around the condyle region of the mandible for all three different implant configurations (Protocol 1, Protocol 2, and Protocol 3). Stress concentrations at the prosthetic bar for all loading conditions were observed around the region where the external force is applied. For all loading conditions and protocols, maximum stresses were found on the neck of the dental implants. Regions over the abutments in close vicinity to the loading area had maximum stress values for all configurations and loading conditions. Stresses over abutments concentrated at the abutment–implant contact region. Maximum stresses over the screws were observed on the neck of the screws for Protocol 1 and Protocol 2 and on the screw–abutment contact region for Protocol 3 for all loading conditions.

Stress values over the mandibles

The mean of the maximum stresses occurred over the mandibles for three different implant configurations and three different loading conditions are shown in Figure 6. It was observed that the lowest von Mises stresses were seen in Protocol 2 for all three loading conditions ($p < 0.016$). The highest stress values over the mandibles occurred in Protocol 3 for chewing force (Figure 6(a)) and in Protocol 1 for both biting and impact forces (Figure 6(b) and (c)).

Stress values over the prosthetic bars

The mean of the maximum stresses over the prosthetic bars under the chewing force was statistically lower in Protocol 2 than in Protocol 1 and Protocol 3 ($p < 0.016$) (Figure 7(a)). On the other hand, the lowest stresses occurred in Protocol 3 for the biting and impact forces (Figure 7(b) and (c)).

Stress values over dental implants

The mean of the maximum stresses over the dental implants under three different loading conditions are shown in Figure 8. It can be seen from the figure that the lowest stresses over the dental implants for the chewing force were obtained in Protocol 1, for biting force in Protocol 3, and for impact force in Protocol 1 ($p < 0.016$) (Figure 8).

Obtained stress values over the long and short implants are separately given in Table 2. It can be observed from the table that the use of short implants substantially reduced the stress levels over the long implants in Protocol 2 for all types of loading conditions ($p < 0.016$).

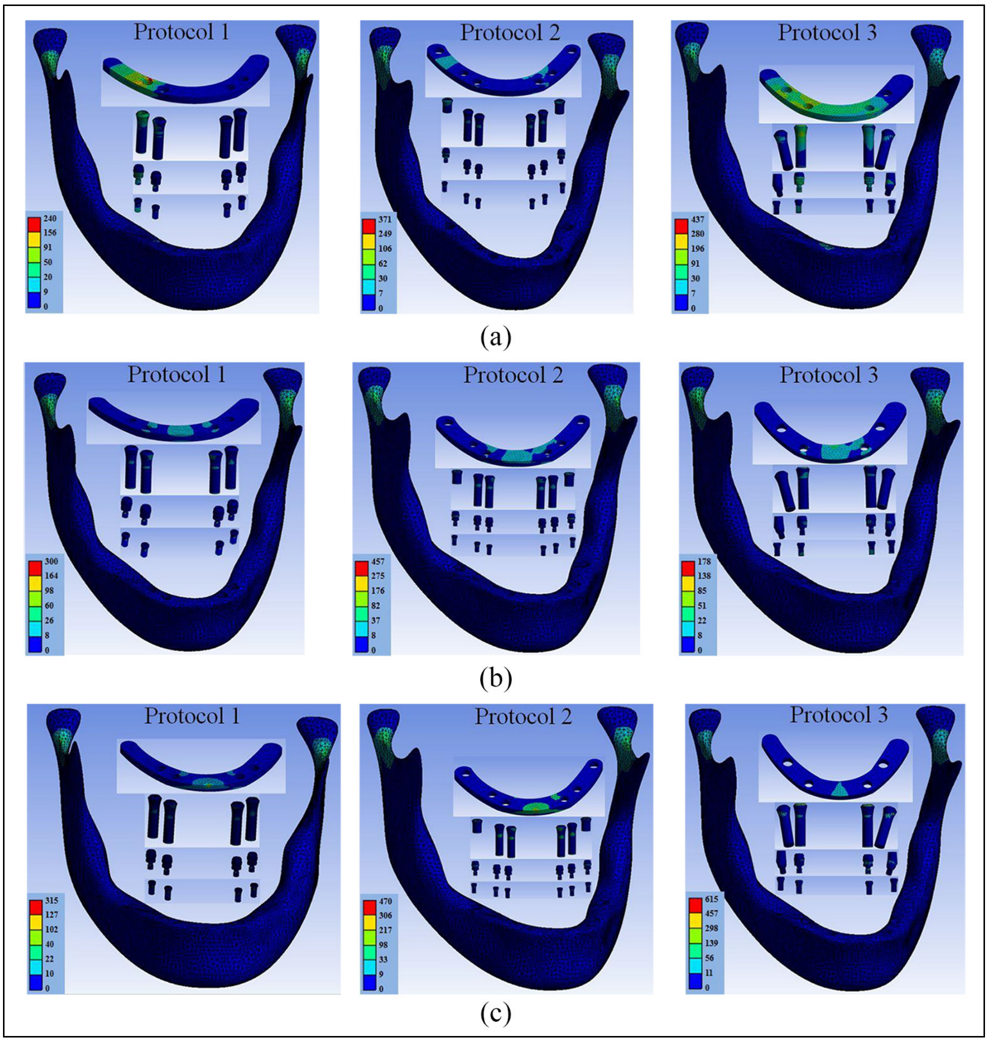

Figure 5. Representative von Mises stress distributions over the mandible, prosthetic bar, dental implant, abutment, and screw under (a) chewing force, (b) biting force, and (c) impact force (all stress values are in MPa).

Stress values over the abutments

The lowest maximum stresses over the abutments were obtained for the chewing force in Protocol 1, for biting force in Protocol 3, and for impact force in Protocol 2 ($p < 0.016$) (Figure 9). The direction and location of the applied forces directly affected the level of the stresses that occurred over the abutments.

Stress values over the screws

The lowest maximum stresses over the screws were obtained in Protocol 3 among three different implant configurations under all types of loading conditions ($p < 0.016$) (Figure 10(a)–(c)). Similar mean maximum stresses were obtained for Protocol 1 and Protocol 2 for both biting and impact forces, but significantly higher stress was obtained in Protocol 2 than in Protocol 1 for chewing force ($p < 0.016$) (Figure 10(a)).

Discussion

In this study, we analyzed the stress distributions of three different implant configurations, which are used for the treatment of mandibular edentulism, under three different loading conditions to determine the biomechanically ideal combinations of dental implants. We found that Protocol 2, which was composed of four long implants and two short implants, led to the lowest stress concentrations over the mandible under chewing, biting, and impact forces, which is an important benefit, especially for the patients with excessive alveolar bone resorption. All stress concentrations over the mandible for all three protocols under three different loading conditions occurred around the condyle of the mandible, which is the most susceptible region to the mandibular fractures.[31] Protocol 2 also resulted in significantly lower stresses than Protocol 3 and Protocol 1 over the prosthetic bars under chewing forces, because

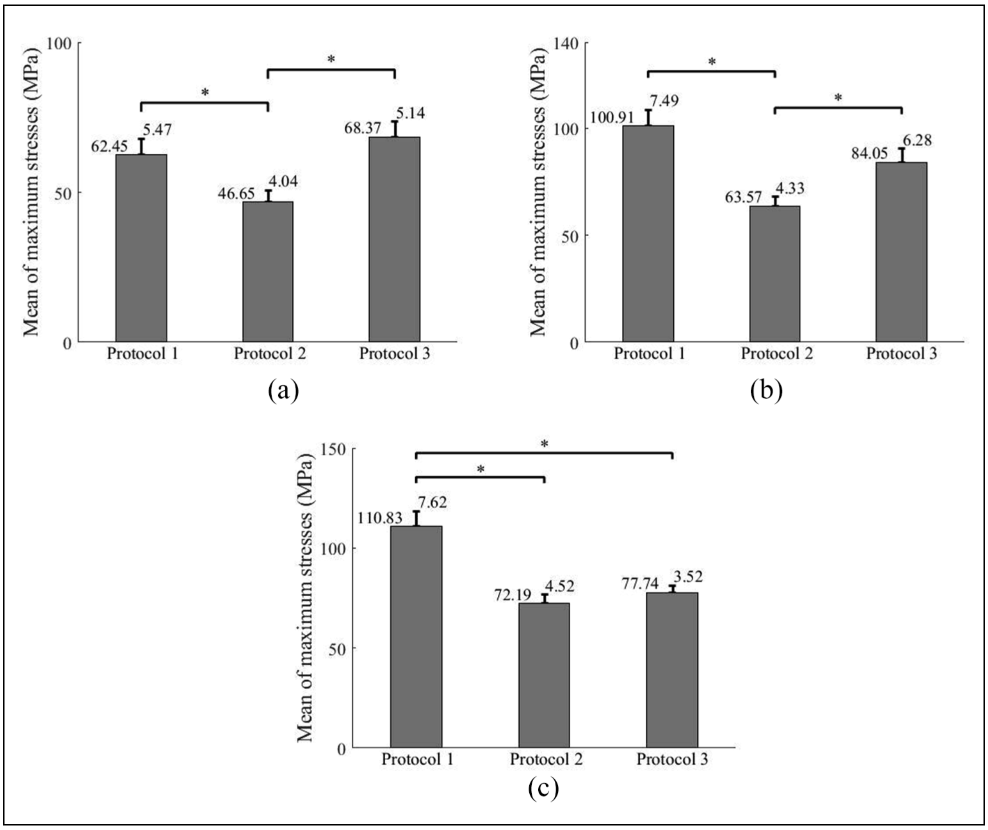

Figure 6. Mean (±standard deviation) values of maximum stresses over the mandibles calculated from 10 models under (a) chewing, (b) biting, and (c) impact forces.
*Statistical significance among intragroup comparisons ($p < 0.016$).

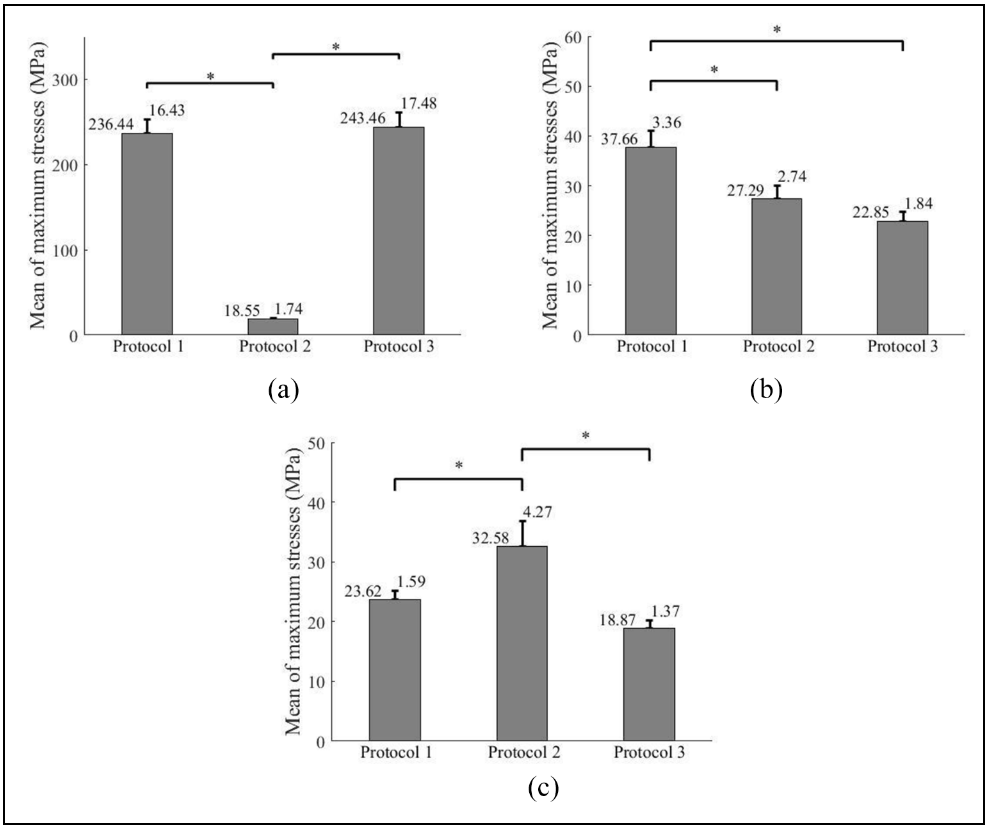

Figure 7. Mean (±standard deviation) values of maximum stresses over the prosthetic bars calculated from 10 models under (a) chewing, (b) biting, and (c) impact forces.
*Statistical significance among intragroup comparisons ($p < 0.016$).

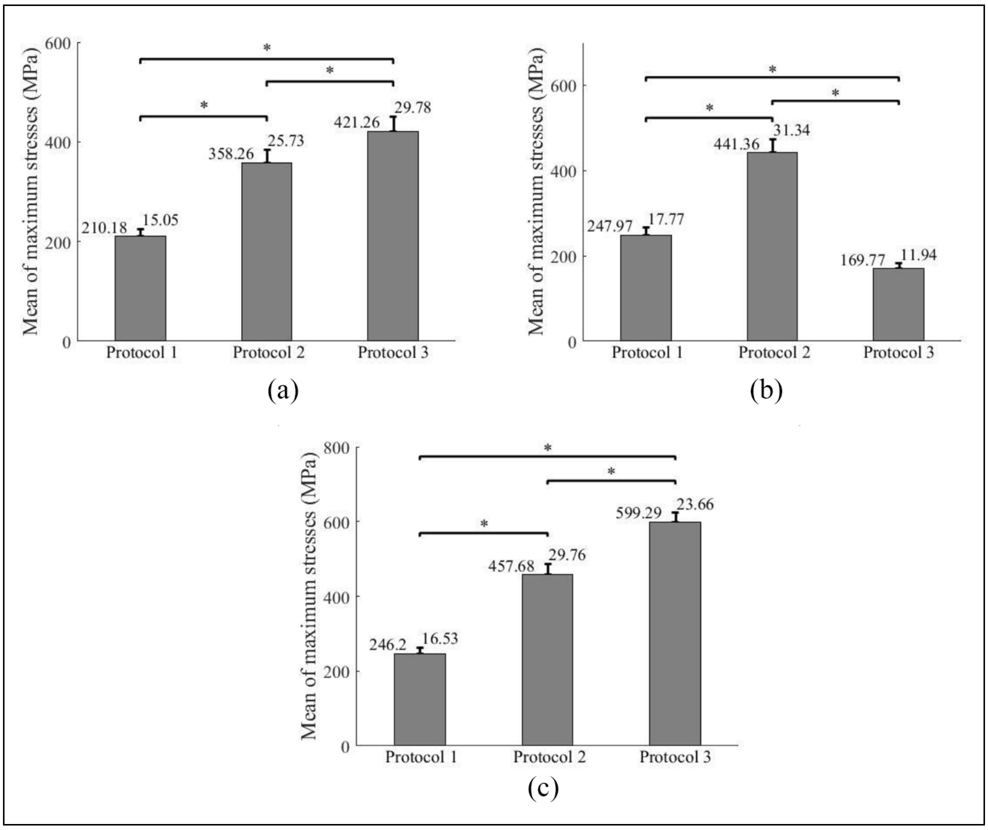

Figure 8. Mean (±standard deviation) values of maximum stresses over the dental implants (including both long and short implants together) calculated from 10 models under (a) chewing, (b) biting, and (c) impact forces.
*Statistical significance among intragroup comparisons ($p < 0.016$).

Table 2. Maximum mean stress values (±standard deviation) over the dental implants obtained from Protocol 1, Protocol 2, and Protocol 3 for three different loading conditions (all values are in MPa).

		Chewing force	Biting force	Impact force
Long implant	Protocol 1	210.18 ± 15.05	247.97 ± 17.77	246.2 ± 16.53
	Protocol 2	156.51 ± 11.38	230.08 ± 16.93	231.62 ± 14.37
	Protocol 3	421.26 ± 29.78	169.77 ± 11.94	599.29 ± 23.66
Short implant	Protocol 2	358.26 ± 25.73	441.36 ± 31.34	457.68 ± 29.76

of the short implants supporting the posterior portion of the prosthetic bar bore a significant portion of the stresses (Table 2). Relatively high-stress values seen over the short implants were compensated by the relatively low-stress values that occurred over the long implants of Protocol 2. We found that none of the implant placement protocols consistently provided the minimum stress distribution over the abutments for all the loading conditions (Figure 9). As for the screws, Protocol 3 was the best option to obtain the lowest stress values (Figure 10).

Rehabilitation of edentulism using dental implant fixed prosthodontics is an accepted and well-known approach. However, excessive alveolar bone resorption, which is common after tooth loss and mainly occurs due to pathologic conditions, complicates the implant therapy.[32] Excessive alveolar bone resorption at the posterior mandibular region causes vertical deficiency due to the anatomic location of the inferior alveolar neurovascular bundle. Clinical studies reported that inferior alveolar nerve damage during dental implant therapy is not rare.[33] Several methods have been described to eliminate the posterior alveolar bone deficiency.[34] Most of them focus on the augmentation of the resorbed bone to restore the normal anatomic shape and volume by means of free block bone grafting, guided bone regeneration, and distraction osteogenesis.[34] These invasive methods are not complication-free options, and generally, they are not well accepted by the patients due to high failure rates, high costs, and

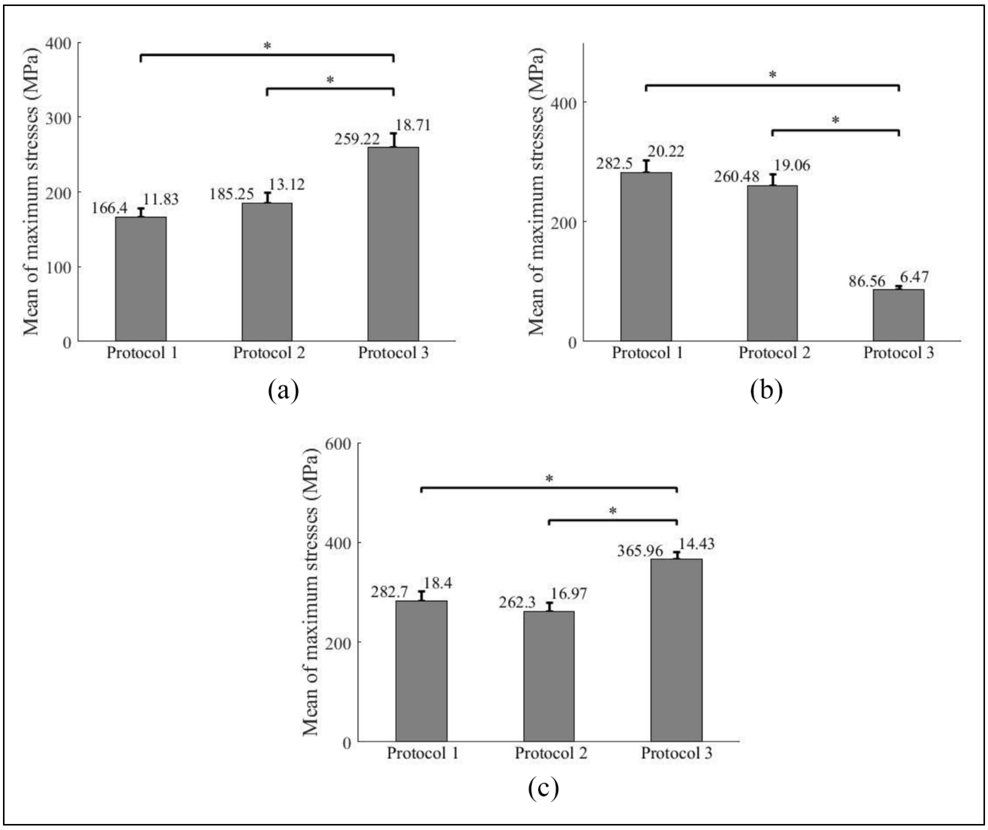

Figure 9. Mean (±standard deviation) values of maximum stresses over the abutments calculated from 10 models under (a) chewing, (b) biting, and (c) impact forces.
*Statistical significance among intragroup comparisons ($p < 0.016$).

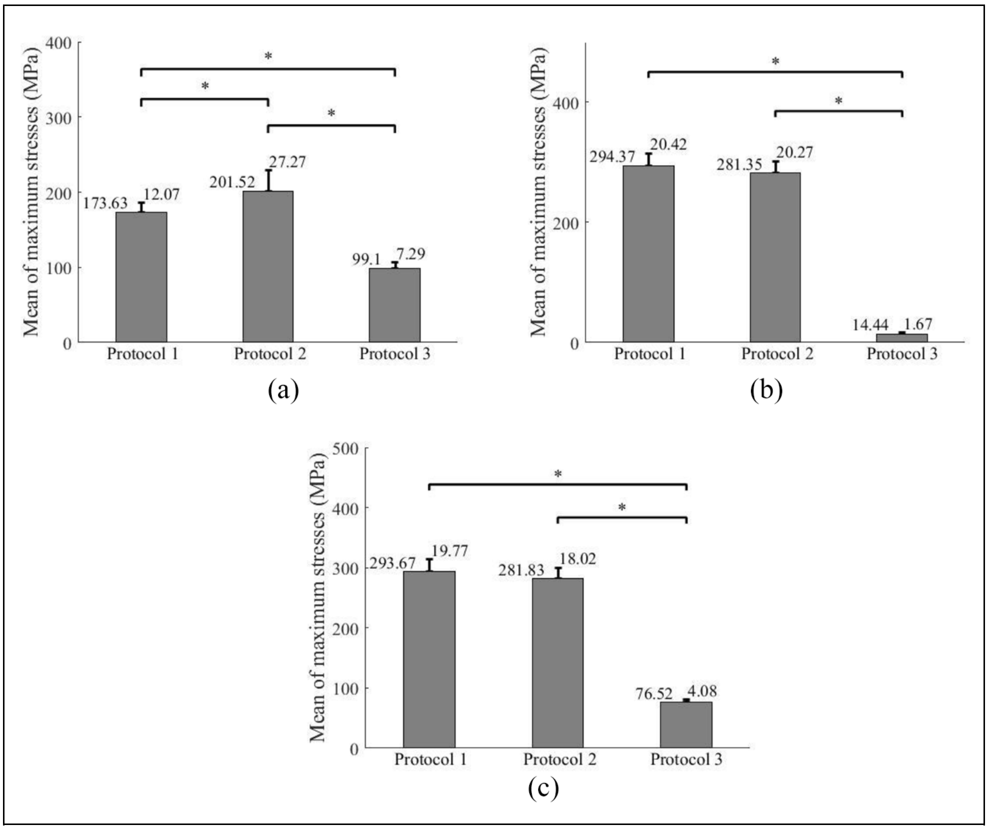

Figure 10. Mean (±standard deviation) values of maximum stresses over the screws calculated from 10 models under (a) chewing, (b) biting, and (c) impact forces.
*Statistical significance among intragroup comparisons ($p < 0.016$).

some surgical difficulties. Using short dental implants or performing the All-on-4 concept may be the simplest alternatives.

The All-on-4 concept is recently introduced by Maló et al.[6] using a specific implant system. Maló et al.[6] asserted that intraforaminally inserted four dental implants are capable of bearing full-arch fixed dental restorations. In this concept, two distally 30° inclined posterior implants placed near the right and left mental foramina and two vertical implants placed to the symphysis region support the cantilevered fixed prosthesis. Although short-term clinical evaluations reported that placement of the angulated implants to manage mandibular edentulism in severe atrophy cases by reducing the distal cantilever length is a useful method, long-term clinical trials evaluating the stress distribution around the implant system components, prosthesis, and implant–bone interface are limited.[6,35,36] On the other hand, using short dental implants may be a useful alternative to manage posterior mandibular alveolar bone atrophy. Although some clinical trials are reporting low success rates, it is now clear that short implants have almost the same clinical success level in comparison with standard dental implants when they are used for the proper indications.[37–39]

Masticatory forces generated during the chewing, biting, or impact forces are transmitted to the bone and surrounding soft tissues by the components of the implant-retained fixed prosthodontics. The stresses accumulated around the bone–implant interfaces are compensated by the peri-implant tissues, provided that the levels of stresses are in clinical limits. However, the stresses higher than the clinically acceptable levels cause alveolar bone resorption and implant fails in long-term follow-ups. Also, higher stress values negatively affect not only the biological structures, but also prosthodontic parts and dental implant system.[40,41] The key factor to protect the peri-implant and prosthodontic elements from the possible damage of excessive stress is to determine the ideal implant localizations. For this purpose, computer-based stress analysis systems are used in dentistry to evaluate the biomechanical behaviors of dental implant–retained prosthodontic treatments under functional forces.[42] Among these computational simulations, the finite element is one of the most common methods to understand the effect of stress distribution over the materials.[26] Although finite element method is a common and useful method, most of the simulated biologic tissues are considered as isotropic, linear elastic, and homogeneous, limiting the reliability of the results. However, besides this disadvantage, the finite element approach offers a practical alternative to study great numbers of subjects with high variability in shapes and dimensions within a relatively short period.[43–45]

The first treatment option that comes to mind for the mandibular posterior alveolar ridge deficiency cases is the placement of dental implants into the intraforaminal region to support distal cantilevered prosthodontics. However, the length of the distal cantilever is directly associated with the stress accumulation on the distal implants and prosthesis, which may cause damage to the prosthesis or alveolar bone resorption and implant failure in the long-term periods.[14] In this study, it was identified that using the All-on-4 system is safe and a useful alternative to reduce to distal cantilever length. In many cases, the All-on-4 system led to lower von Mises stress values than Protocol 1, indicating that the obtained results of this study are in agreement with those reported by Maló et al.[6,36]

Despite the implant length is one of the major factors affecting the long-term stability by increasing the bone–implant contact surface area, it was reported that there was no direct relationship between the stress distribution on the crestal bone–implant interface and the implant length.[46,47] As a result, using short dental implants at the distal sites in combination with intraforaminally placed standard implants may be a useful approach to manage mandibular posterior alveolar bone deficiencies. In this study, we observed that Protocol 2 resulted in lower stresses than Protocol 1 and Protocol 3 over the mandibles and prosthetic bars. By taking these results into account, we consider that the failures related to the stress accumulation may be reduced using Protocol 2 rather than Protocol 1 and Protocol 3 in the long-term follow-ups.

In addition to differences between the stress levels of the investigated protocols, there is also diversity about treatment costs. The All-on-4 concept requires using some special units such as Multi-Unit abutments (Nobel Biocare AB) and precise dental laboratory labor for the fabrication of screw-retained fixed prosthodontics. It is suggested to perform immediate loading right after the placement of the dental implants and it requires providing special screw-retained provisional dentures, which causes extra costs.[48,49] Although using two more short implants in addition to four intraforaminally placed implants increases the total cost of treatment, this additional expense is relatively lower than the extra costs of the All-on-4 concept.

There are several limitations to this study. First, we sought a trade-off between model complexity and computational efficiency. As a result, to reduce the computational time, the mandible models were assumed to have linear elastic, homogeneous, and isotropic characteristics which would affect the accuracy of the obtained results. Second, for having an objective comparison between the implant placement protocols, consistent positioning of the implants on the mandible models is crucial. The locations of the implants on the mandibles were determined to make them consistent with the clinical aspects. And finally, the applied loads were treated as static. Thus, the fatigue behavior of the implants caused by dynamic loading was disregarded.

Conclusion

We concluded that using the combination of four anterior and two short posterior implants (Protocol 2) is biomechanically more ideal than Protocol 1 and All-on-4 concept (Protocol 3) to manage the posterior edentulism in severe atrophy cases. On the other hand, if it is not possible to use short implants because of insufficient bone tissue in the posterior region of the mandible, angled implants used in the All-on-4 concept would provide more homogeneous stress distribution than the system where the implants are placed vertically to the mandibular intraforaminal region (Protocol 1). We suggest future clinical trials to evaluate these treatment modalities in real cases.

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Declaration of conflicting interests

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