Journal of Oral Biology and Craniofacial Research 14 (2024) 284–289

Contents lists available at ScienceDirect

Journal of Oral Biology and Craniofacial Research

journal homepage: www.elsevier.com/locate/jobcr

A comparative evaluation of masticatory load distribution in different types of prosthesis with varying number of implants: A FEM analysis

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ARTICLE INFO

Keywords:
Implant-supported overdentures
Von mises stress
Complete denture
Bar-supported
Finite element analysis

ABSTRACT

Aim: To identify the optimal number and position of implants to reduce stress concentration on the implant, denture, and attachment system for sustaining an overdenture prosthesis.

Materials and methods: By incorporating one to eight indigenous implants with bar-type attachments, eight 3D finite element models of mandibular overdentures were created. All models received a 200 N vertical load, and the biomechanical characteristics of peri-implant bone were assessed.

Result: The study observed that with a vertical load of 200 N, the maximum equivalent stress around peri-implant tissue in all models was within the physiological tolerance threshold of bone. The von Mises stress values ranged from 116.18 MPa to 536.7 MPa.

Conclusion: The three-implant-supported overdenture model revealed superior peri-implant stress, stability, cost-effectiveness, and hygiene maintenance outcomes. Placing a third implant in the mid-symphysis region may offer a practical solution to reduce rotations in two-implant-supported overdentures.

1. Introduction

Losing natural teeth hinders an individual's capacity to lead an everyday personal and social life since it limits masticatory ability, impairs neuromuscular coordination, alters speech, and impacts esthetics. One standard treatment option for edentulism is conventional complete denture treatment. Residual ridge resorption is inevitable and an inherent part of the procedure, leading to complete denture loosening owing to inadequate denture fit. The intaglio surface of mandibular dentures and the tongue influence the mandibular area; these lead to displacement of the prosthesis during mastication and speech. Studies have shown that patients wearing complete dentures experience reduced masticatory function, leading them to avoid certain hard foods and affecting their nutrition.[1,2] Using an implant-retained overdenture to rehabilitate an edentulous mandible has become a standard procedure that greatly benefits edentulous patients.[3] Two implant-retained overdentures are commonly favored in the mandible. However, some studies indicate that adequate retention and success can be achieved with a single implant-retained overdenture.[3–5] The surrounding tissues undergo less stress in overdenture retained with two implants compared to a single implant-retained overdenture, irrespective of the implant type.[6] According to recent studies, there are no substantial differences in overall success between a one-implant compared with a two-implant overdenture.[7]

The implant-retained overdenture with three or four implants does not have a parallel relationship between the implants. This angular relationship provides additional support in the anterior region, especially in highly resorbed ridges, prominent mylohyoid ridges, or in patients with high muscle attachment. Two implants retained overdentures are more common than other choices, even though using more than two implants in the edentulous mandible had a high success rate.[8–11] In All-on-four prostheses, four implants are generally placed in cases with highly resorbed edentulous jaws with less vertical bone height available in the posterior region. In the maxilla, two straight implants in the anterior region engage the nasal cortex, and two posterior tilted implants along the anterior wall of the maxillary sinus are placed. In the mandible, two straight implants in the anterior region and two posterior tilted implants mesial to the mental foramen are placed in the treatment process. The study showed that this treatment success rate in the mandible is as high as 98.1 %, and it is a long-term viable solution.[12] The edentulous ridges that are highly resorbed can also be rehabilitated with hybrid prostheses. The hybrid prosthesis replaces

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https://doi.org/10.1016/j.jobcr.2024.03.010
Received 20 November 2023; Received in revised form 15 March 2024; Accepted 17 March 2024

both the teeth and the resorbed bony tissue. They provide minimum stress to the underlying structures as it has a dampening effect. A fixed hybrid prosthesis with at least six implants or more extends the anteroposterior (A-P) spread and reduces the cantilever to achieve the highest benefit.

Therefore, the type of prosthesis that is better for masticatory load distribution and stress concentration in the peri-implant region in edentulous patients is still up for discussion. This study used finite element modelling (FEM) analysis with three-dimensional (3D) models to compare bone stress between implant positions for mandibular overdenture prosthesis, All-on-four prosthesis, and hybrid prosthesis with vertical load orientation in a specific boundary condition.

2. Material and method

2.1. Model design

A computed tomography (CT) examination was carried out on a volunteer to obtain the geometry of an edentulous patient's mandible, with approval from the Institutional Research Ethics Committee (Letter no. Dean/2021/EC/2704, Dated June 23, 2021). The mandible and mandibular overdenture were scanned. The CT examination files were then imported into Mimics 8.0 (Materialize, Leuven, Belgium). Indigenous implants (made in the Faculty of Dental Sciences; diameter: 4.2 mm, length: 10 mm, screw-shaped two units with morse taper internal attachment of one degree; friction fit) and bar attachment systems (diameter: 5.00 mm) were chosen as overdenture retainers for this biomechanical analysis (Fig. 1). The three-dimensional geometries of the edentulous mandible and prosthetic components were modelled in SolidWorks 2008 (Solid Works Corporation, Ve' Lizy Villacoublay, France). The geometries of the mandible, overdenture, implant and attachment systems were then meshed using Version 11.0 of Hyper Mesh CAE. Eight 3D finite element models of an edentulous mandible supporting an implant overdenture were designed, each with different numbers and positions of implants in the mandible. All implants were vertically positioned and well distributed in the mandibular region, as follows.

- Group A-conventional denture
- Group B- single implant overdenture

The implant in this group was placed at the mid-symphyseal region.

Fig. 1. Indigenous implant used in study.

- **Group C**- two-implant overdenture

The implants in this group were placed in the canine region.

- **Group D**-three-implant overdenture

The implants in this group were placed at the symphyseal region and two at the canine region.

- **Group E**-four-implants-supported prosthesis

There are two on each side of the canine and molar regions.

- Group F- All-on-four prosthesis
- **Group G**-six-implant-supported prosthesis.
- **Group H**- eight-implant-supported prosthesis

The models were meshed with 3D four-node tetrahedron elements. The total numbers of elements and nodes are listed in Table 1. A refined mesh was generated in the mandibular region to faithfully reproduce the complex strain distribution observed in peri-implant bone. The ANSYS 20.1 version, which can import models with 100% data transfer or with 0% data loss, was used for this study.

With ANSYS 20.1, all of the components were independently modelled and integrated to construct 3D models of the mandible that depicted different implant positions and numbers with different prostheses (Fig. 2A–H).

2.2. Material properties

The mandibular model was made up of a 2-mm thick mucosa covering a cancellous bone core and a 2-mm constant cortical bone layer. According to the group, titanium implants measuring 4.2 mm in diameter and 10 mm in length were positioned in the prescribed locations. Both the implant and the abutment were constructed from titanium alloy Ti6Al4V. The 5 mm wide bar attachment went all the way to the posterior implant. The values were used as per the literature to determine the material qualities of the mucosa, cortical bone, cancellous bone, and prosthetic components.[3] All substances were taken to be homogenous, linearly elastic, and isotropic (**Table 2**).

2.3. Contact management and loading conditions

The implant's osseointegration was deemed complete. As a result, it was assumed that the interface between the implant and the bone was mechanically flawless. However, when functioning, the overdenture's interaction with the mucosa was not fixed. Instead, numerous directions of rotation and sliding on the mucosa were possible for the overdenture. We assumed that there was sliding friction between the overdenture and mucosa to mimic this displacement. The overdenture and mucosa's coefficient of sliding friction was fixed to 0.334. In all degrees of freedom, the models were restrained at the nodes on the mesial and distal bones. Models' dentures and overdentures in the region of the molars were subjected to a single 200 N vertical stress, as the primary force is the

Table 1
Nodes and elements.

Groups	Elements	Nodes
Group A	30786	56570
Group B	32767	61447
Group C	37777	72316
Group D	41538	80512
Group E	49432	95914
Group F	49892	96824
Group G	57751	113928
Group H	70966	139980

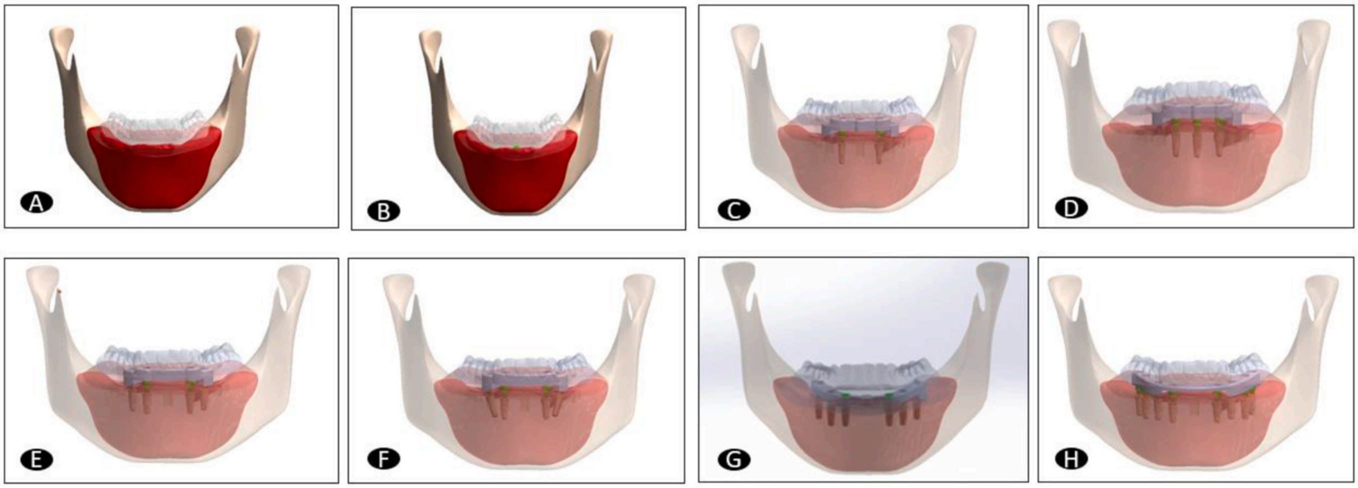

Fig. 2. A to 2H: The four 3D finite element models of the edentulous mandible and prosthetic components: (A) represents model A (complete denture); (B) represents model B (single-implant model); (C) represents model C (two-implant model); (D) represents model D (three-implant model); (E) represents model E (four-implant model); (F) represents model F (four-implant all-on-four model); (G) represents model G (six-implant model); (H) represents model H (eight-implant model).

Table 2
List of the materials with their physical properties.

S. No.	Material Name	Density (G/cm3)	Youngs Modulus (Mpa)	Poissons Ratio
1	cortical bone	1.35	1370	0.3
2	cancellous bone	0.92	1370	0.3
3	Gingiva	1	200	0.45
4	Mucosa	1.1	680	0.45
5	titanium alloy	4.62	1.10E+05	0.3
6	acrylic resin base	0.00118	1960	0.3

compressive force. Prior to the simulation, the FEA models were marked with fixed points through the long axis of the mandible to accurately determine the deformation and stress on the models.

3. Result and Observation

On application of 200 N vertical load over 8 model designs, the single implant group showed the lowest values of the maximum von Mises stress of 116.18 MPa (megapascal), and the highest value of von Mises stress was shown by the eight-implant supported overdenture group of 536.7 MPa. The three implant-supported rehabilitation with bar-retained overdentures demonstrated a good outcome according to the current analysis.

The obtained deformation and stress values are mentioned in Table 3 and Fig. 3A–H according to respective groups. The complete denture model, group A, has a maximum von Mises stress of 199.24 MPa. The highest von mises stress determined for the group B model, which had a single implant retained overdenture, was 116.18 MPa, which was less than the value for the complete denture model. In comparison to group B, group C showed a higher maximum stress (486.01 MPa) due to two implant-retained overdentures. The maximum von mises stress around the periimplant bone in the overdenture of group D, which had three implants, was 247.57 MPa, a value less than in the two implant models. The highest von Mises stress value in group E, which comprised four implant-supported overdentures, was 424.36 MPa. In group F, with 4 implant supported overdenture in all-on-four configuration, the assessed values of maximum von mises stress was 389.92 MPa, lesser than group E model. The 6 implant supported overdenture in group G the equivalent stress generated around the implants was 454.68 MPa. The overdenture model of group H supported by 8 implants, the peri implant von mises stress generated was 536.70 MPa, highest of all the groups.

Table 3
Results and observations.

GROUPS	Number of teeth	Von miss stress per implants (MPa)	Maximum equivalent stress (MPa)
Group A	28	No Implant	199.24
Group B	28	Implant 1–4.8502	116.18
Group C	28	Implant 1–6.1826	486.01
		Implant 2–6.8571	
Group D	28	Implant 1–4.5911	247.57
		Implant 2–4.9634	
		Implant 3–6.2125	
Group E	28	Implant 1–3.6605	424.36
		Implant 2–2.8528	
		Implant 3–3.9438	
		Implant 4–3.6017	
Group F	28	Implant 1–3.3582	389.92
		Implant 2–4.6101	
		Implant 3–4.1222	
		Implant 4–2.5293	
Group G	28	Implant 1–6.9337	454.68
		Implant 2–6.5855	
		Implant 3–3.4844	
		Implant 4–8.8201	
		Implant 5–3.7641	
		Implant 6–4.0796	
Group H	28	Implant 1–5.4364	536.7
		Implant 2–3.9491	
		Implant 3–3.8340	
		Implant 4–11.688	
		Implant 5–10.541	
		Implant 6–5.8309	
		Implant 7–5.8307	
		Implant 8–7.0733	

4. Discussion

The long-term successful outcome of therapy with osseointegrated dental implants depends on how the loads are transferred from the implant to surrounding bone tissues and dissipated therein. The factors that may influence the stress dissipation in the bone tissue include the amount and direction of the load, implant position and angulation, the characteristics of the implant surface, the design and size of the implant, the type of prosthesis, the type of prosthetic connection; and the quantity & quality of bone tissue. The two main types of forces operating on the implant are axial and oblique forces. The axial force evenly distributes tension along the implant axis, which is better for the implant's longevity; in contrast, the oblique force creates more tension in both the

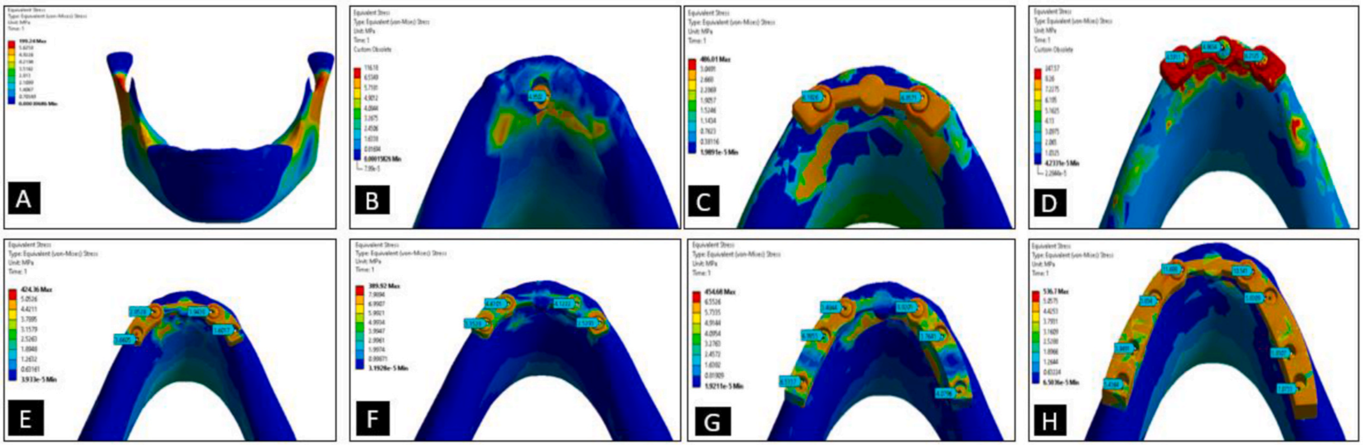

Fig. 3. A to 3H: Equivalent strain distribution in the peri-implant bone of model A, B, C, D, E, F, G, and H under a 200 N vertical loading condition. Colours indicate level of strain from dark blue (lowest) to red (highest).

implant and surrounding bone tissue. Therefore, we always create an occlusal scheme where functional cusps of the posterior teeth contact the opposing teeth in a centric holding location and no deflective contact on the slants is given to avoid the tension or shear or couple forces for the long-term survival of the implant. Similarly, in anterior teeth, the occlusal scheme with no contacts in the centric relation position and group function with light contact in the eccentric position is established.[13,14]

FEM analysis is a technique of analyzing numerical stress that is frequently employed to research engineering and biomechanical issues. It accurately and mathematically represents complicated geometries and is easily adaptable to changing assumptions. As the method can simulate both isolated vertical, horizontal, oblique, and couple load/stress, it is an accurate and useful tool for testing dental implant systems. Although, the inherent limitations of the FEM analysis concerning stress/strain distribution need to be considered. The models used in this FEM study deviate from the in vivo conditions prevailing in the mouth, especially the fact that the tissues are not homogenous and neuromuscular control is there in the oral cavity, which is not simulated here. All of the models in this study presupposed the homogeneous, isotropic, and linear elastic nature of the structures. To select amongst various overdenture designs, all on four techniques or implant-supported fixed prostheses for full arch rehabilitation in clinical therapy, the data obtained in this study should be taken into consideration. Further, to validate the findings of this study, prospective clinical investigations are required as there is a gap between computer simulation and in vivo scenarios.[15]

According to the findings of this investigation, maximal equivalent stresses in peri-implant bone under 200 N load were not more than 878.87 MPa in all models, which is below the elastic modulus of bone. This research supports earlier clinical studies that found no discernible difference in the rate of peri-implant bone resorption between overdentures supported by a single implant, two implants, three implants, and four implants. This suggests that the stress around the peri-implant bone was within the range of the physiological tolerance limit and had only a slight impact on the implant survivability.[16–18]

Clinicians anticipated that on increasing the number of implants, the peri-implant bone's maximum stress value would decrease as the stress would be distributed more uniformly throughout the bone.[19,20] Theoretically, as additional anchoring and supporting implants were added, the force carried by each implant would weaken, and the stress on the bone would decrease. This research indicates that as the number of implants in groups C, D, E, F, G and H increased, the von Mises stress value in the peri-implant bone increased when compared to group B. This can be explained by the fact that with an increase in the number of implants, the masticatory stress shared by each implant is higher than the bone and underlying mucosa. In support of the present work, Liu et al. also discovered that the amount of stress in the peri-implant region increased as the number of implants increased.[3]

There has been some worry that three implant-supported overdentures may place excessive stress on the bone surrounding the middle implant, particularly when used with the posterior teeth. However, when an equal bilateral load of 200 N was applied to the models, it was found that the middle implant of an overdenture supported by three implants did not put any significant strain on the cortical bone. Additionally, when using ball or bar attachments, Geckili et al. found that the central implants of three implant mandibular overdentures experienced less marginal bone loss than the implants on the left and right sides.[21] As a consequence of our research, we were able to determine that the three-implant overdenture was the most stable implant model. This may be supported by the fact that the middle implant makes the overdentures more stable and reduces the strains. Patients who complain about rotational movement around the fulcrum line of a two-implant mandibular overdenture could theoretically benefit from the inclusion of a third implant in the midline of the jaw to boost denture stability. Retrospective studies done to clinically compare the masticatory efficiency of the two and three implant-retained overdentures conclude no significant difference between the two situations.[10,20,22,23] Comparing the four-implant-supported overdenture group with the three-implant-supported overdenture group, it was discovered that the latter group created increased maximum stress surrounding the implants. Junior et al. demonstrated a higher success rate in rehabilitation carried out with the prosthesis installation on three implants, irrespective of the loading.[18] To better understand how loading affects the clinical performance of overdenture prostheses supported by three implants, more research needs to be done.

Installing more than five dental implants for rehabilitation with a mandibular implant-supported prosthesis typically produces good clinical outcomes. Success has also been noted when the prosthesis is positioned on four implants. However, dental implant installation may be hampered in clinical settings by factors such as a lack of bone at possible implant locations. Another scenario to take into account is the possibility of installing four or more implants initially but later losing implants, which may result in difficulty in further prosthetic rehabilitation.[24]

When comparing the results of four implant-supported overdenture and all four types of prosthesis, it was found in the present study that the values of the equivalent stress were more around the peri-implant bone with all four configurations, with the difference between the stresses being non-significant.

The posterior implants displayed the lowest values when the stress pattern for each individual implant in group F was examined. A study conducted by Durkan et al. also showed the same result that the use of angled standard posterior implants showed the lowest values of von Mises stress in the posterior region of the peri-implant bone area. He also studied that although the straight implants model showed more von Mises stress in the bone around the implant, the stress values in the bar screws and abutment screws were lower for the straight four implant model.[25] Therefore, it can be concluded that even though the peri-implant bone overload occurs in straight implant models, the risks of prosthetic failure are higher for the 45-degree titled four implant model.

According to the results obtained, it can be stated that the stresses generated around all the implants supporting the overdentures (Group B to E) were lesser as compared to the peri-implant region of the anterior implants in (Group G and H). The stresses generated in each posterior implant of Groups G and H were negligible as none of the implants experienced more than 0–3% stress of the total von Mises stress. This increased stress for the anterior implants may be because of overdentures supported on the implants were not fixed. Therefore, upon applying the load in the posterior area, the rotation of the overdenture around the anterior implants caused an increase in stress (torsion and tension). Previous studies have also stated that, although the fixed prosthesis is psychologically well accepted by the patients in terms of comfort and stability, overdentures are no less efficient than fixed prostheses in terms of implant stability and bone resorption. Also, the overdentures can be more advantageous over the fixed prosthesis in terms of reduced plaque index and probing depth as they are easier to clean.[19,26,27]

Considering the restrictions of the current FEM analysis study, the use of three straight splinted implants supported overdenture with twelve occluding units can be considered a good prosthetic option clinically in terms of stability, support, reduced prosthetic complications, implant survival rate, crestal bone loss, cost-effectiveness, patient satisfaction, cleanliness and hygiene.

Limitations

- It is a computerized in vitro study — the clinical condition may not be completely replicated as the cortical bone of the jaw is inhomogeneous and transversely isotropic, nonetheless, as is well-known. Additionally, a 100% implant/bone contact was made, which is not consistent with the clinical situation.
  •Stress analysis is under static loading, and the mechanical properties are set as isotropic and linearly elastic.

Conclusion

It is possible to conclude, in light of the research question, that-

- The three implant-supported rehabilitation with bar-retained overdentures demonstrated a good outcome according to the current analysis and have similar clinical data about post-loading implant loss.
- The implant that was positioned in the mid-symphysis area of the three-implant supported overdenture holds significance as it lowered the peri-implant stresses by decreasing denture rotation along the fulcrum line crossing two bilateral implants.

Clinicians should suggest removable choices to patients instead of favouring fixed prostheses. The majority of the time, patients have a psychological tendency to choose the permanent fix alternative, but when properly advised, they will choose a removable prosthesis. Clinicians should refrain from using complex screw-retained fixed prostheses and put the needs of their patients before their financial interests.

Source of funding

Funding information: Department of Science and Technology (DST), Government of India

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