ORIGINAL ARTICLE

Comparative finite element analysis of external and internal hex connections in mandibular All-on-4 implants under axial loading

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ABSTRACT

Background

The biomechanical performance of implant–abutment connection designs plays a crucial role in the long-term success of all-on-4 implant-supported prostheses. External hex connections (EHCs) and internal hex connections (IHCs) differ in geometry, load transfer, and mechanical stability, which may influence stress distribution and the likelihood of mechanical complications.

Materials and Methods

A three-dimensional finite element model of a mandible with an all-on-4 implant configuration was developed. Two connection designs—EHC and IHC—were simulated with identical implant positioning and prosthetic frameworks. A static axial load was applied to the distal cantilever region. Stress distribution was analyzed in key components including prosthetic screws, multi-unit abutments (MUAs), implant screws, and fixtures. Peak von Mises stress values were compared between the two connection groups.

Results

Both EHC and IHC configurations demonstrated biomechanical stability under axial loading. In both groups, the highest stress concentrations were observed in the prosthetic screws, followed by MUAs, indicating potential weak points in the posterior implants. The EHC group exhibited significantly lower peak stresses in critical components: the implant screw showed 37.75% lower stress and the implant fixture showed 33.03% lower stress compared to the IHC group. Overall, EHCs demonstrated more favorable stress distribution characteristics. Conclusion: External hex connections may offer biomechanical advantages over internal hex designs in all-on-4 mandibular prostheses by reducing stress transmission to implant screws and fixtures. Although both connection types performed within clinically acceptable limits, the reduced stress in the EHC group highlights its potential to minimize mechanical complications. Further experimental and clinical studies are recommended to validate these findings and support optimization of implant–abutment connection designs for full-arch restorations.

Keywords

All-on-4 implants, finite element analysis (FEA), implant–abutment connection, stress distribution, hex connectiona

INTRODUCTION

In order to maximise the use of the remaining bone in atrophic jaws and enable rapid function, the “all-on-four” treatment concept was created. This approach avoids regenerative therapies, which raise treatment costs and patient morbidity and have inherent difficulties [1]. The process supports a four-implant, temporary, fixed, and quickly loaded prosthesis in the anterior site of jaws that are completely edentulous. In order to decrease the length of the cantilever and make use of it for multiple teeth (upto 12 teeth), the 2 posterior implants are positioned distally and at an angle, while the two 2 anterior implants are positioned axially [2]. This improves masticatory efficiency. The following tendencies were preceded by the initial Brånemark surgical-prosthetic protocol, which recommended putting 6 fixture of implants over the mandibles with mild to medium resorption and four fixture of implants to repair a resorbed mandible [3]. Both patients and therapists currently frequently use immediate loading techniques for edentulous jaws. Regardless of the loading protocol used, high survival rates and a low incidence of complications show that implant treatment is predictable. Today, creating straightforward and affordable protocols is the difficulty rather than proving functionality [4].

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Both patients and professionals are increasingly using immediate loading techniques for edentulous jaws [5, 6]. Regardless of the loading strategy used, high survival rates and a low frequency of problems show that implant treatment is predictable [7, 8]. The present challenge is not to demonstrate functionality, but to develop inexpensive and user-friendly protocols.

Complete edentulism can be difficult, and aspects including denture stability and appearance may affect patients' happiness with standard complete dentures [10].

Maló et al. in 2003 developed a therapy strategy known as "All on 4" to address these problems. This method supports a full-arched fixed denture with 4 implants: 2 vertically positioned in the anterior site and 2 slanted in the posterior site. The All on 4 treatment method has the advantages of preventing extra bone grafting operations, reducing cantilever length, and protecting against injury to the inferior alveolar nerve.

Completely edentulous mandibles can be successfully and sustainably rehabilitated with All on 4 therapy. According to a previous study, the pooled overall success rate of the All on 4 therapy was 91.7% up to a 1 and half year follow-up [5]. Also, a study of the literature [7] shown that All on 4 therapy has success rates comparable to traditional vertical implants, mainly due to its favorable biomechanical properties.

A comprehensive literature review indicates a variety of factors, such as the surrounding bone's quantity and quality, dimensions of implant (length, diameter, shape, surface structure, loading type, material properties) affect the distribution of load at the implant - bone interface [11]. Different implant designs with its geometry in implant–abutment connection, might also influence occlusal force transfer. The performance and preservation of osseointegration of implant may be impacted by these design variations, which could result in mechanical and biological problems that could jeopardize prognosis and may leads to implant breaks [12]. Depending on type of connection between the implant and the abutment, implant designs can be classified as internal or external. External connections simplify the prosthetic phase by offering two benefits: improved fit and increased versatility in situations involving multiple replacements of teeth. The most popular surgical technique for the All on 4 therapy, created by Maló et al. in 2019, is the external hexagon connection. Internal connections, on the other hand, typically encourage more equitable distribution of stress and cause less marginal bone loss. However, there are certain disadvantages to both kinds of implant–abutment interactions. While internal connections may pose difficulties in attaining a perfect passive fit with numerous

implants, external ones are vulnerable to biomechanical complications brought on by dislodging abutment, which may generate issues throughout the prosthetic phase [13].

The All on 4 treatment was shown to be viable by Maló et al. in 2019 [14], however all other therapy employed the similar type of implant–abutment connection. The application of exterior and internal hexagon connections as two different types in full-arch rehabilitations was investigated in a different randomised, split-mouth trial. Within a three year follow-up, their results showed that both the two types were linked to increased success rates; however, zero significant differences were noted with mechanical difficulties, likely due to the small sample size [15]. The biomechanical performance of the All on 4 therapy has since become the main focus of research. Reducing the peak bone stress brought on by occlusal loading is a major bioengineering concern with this treatment. The effects of posterior implants' cantilever length, location, and angulation have been the focus of numerous studies [16].

Because of the good survival rates and minimal incidence of problems that show that implant therapy is predictable independent of loading regimen, immediate loading treatments for edentulous jaws have gained popularity among both doctors and patients [17]. Developing user-friendly and reasonably priced protocols is the current challenge, not proving capability. For evaluating and improving the biological and mechanical performance of multiple implant prosthetic therapies, such as All on 4 treatment, Finite Element Analysis (FEA) has shown promise [18]. FEA is a reliable method for modeling several parameters in a prototype, enabling for the examination of their possible applicability in real clinical settings.

2. MATERIALS AND METHODOLOGY

The selected design is suitable to analyze clinically durable under different loading conditions, stress at different components under different loading conditions. The study includes 24 typical models of mandibular All on 4 therapy. Two groups were formed out of them. We chose implants in the external - hexagon connection

(E-HC) group that were 4 mm x 18 mm (diameter x long) (NobelSpeedTM Groovy, Nobel Biocare) [9]. Internal - hexagon connection (I-HC) group utilized implants measuring 4.3 mm x 18 mm (diameter x length) (NobelParallelTM Conical Connection, Nobel Biocare) [9].

To make sure the sample is representative of the larger population, random sampling will be used. Sample size determination was conducted using the MetSizeR approach, a method tailored for high-dimensional data such as metabolomics. The sample size was calculated to achieve a statistical power of 80-90 %, resulting in a requirement of 12 models per group. This sample size

is adequate to detect significant differences in biomarker levels between the groups while maintaining control over the FDR.

The formula used for sample size estimation was: (1)

In this formula:

- The Z-score that corresponds to the significance level is $Z\alpha/2$, which is typically 1.96 for a 95% confidence level.
- The Z-score that corresponds to the necessary statistical power is $Z\beta$, which is typically 0.84 for 80% power.
- $\sigma 2$ represents the variance of the representative models,
- $\mu 1-\mu 2$ is the effect size or the expected difference between the means of the two groups.

2.1 Parameters under study

Clinically durability under the tested loading conditions.

Implant success and failure

Von Mises stress values

Von Mises stress peak values for the

bar of implant

prosthetic - screw

MUA

implant - screw

fixture of implant

Bone

other components

Pattern of stress distribution

The way the load is transferred through parts of the 3D model may affect the patterns of stress distribution. The pattern of stress distribution in both the groups that includes,

bar of implant

prosthetic - screw

MUA

implant - screw

fixture of implant

bone

Response variables

· Material/surface modification of the abutment screw

· loss of preload in the prosthetic - screw

· design of the implant/abutment joint

· method of torque

· cantilever

· misfit of the prosthesis

2.2 Data collection and research tools

Physical domain

The current study examined a representative model of All on 4 therapy in mandible. 2 anterior implants were positioned according to plan in the anterior portion of the model, while 2 posterior implants were positioned in the premolar region. All of the crucial elements of the All on 4 assembly, such as prosthetic - screws, implant - screws, multi-unit abutments (MUAs), and a specially designed titanium framework (bar of implant), were also included in our analysis. Figure 1 illustrates every part of the All on 4 assembly used in our investigation.

The model under examination for the anterior implants includes implants with 4mm diameter x 13 mm length (NobelSpeedTM Groovy) [9] and a straight abutment of 1 mm (Multi-unit Abutment, Nobel Biocare). Two types of implant abutment connections were employed for the posterior implants. The implants we selected for the external hexagon connection (E-HC) group were 4 x 18 mm in diameter x length (NobelSpeedTM Groovy, Nobel Biocare) [9]. The internal hexagon connection (I-HC) group's NobelParallelTM Conical Connection implants were 18 mm long and 4.3 mm in diameter [9]. We chose 30° angled abutments (30° Multi-unit Abutment, Nobel Biocare) for both groups. To ensure

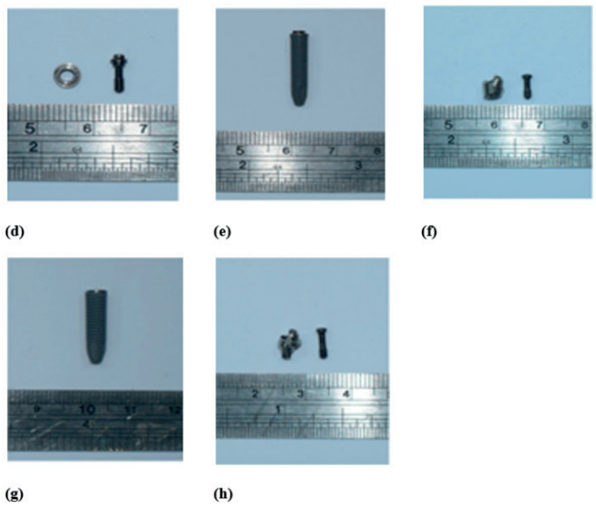


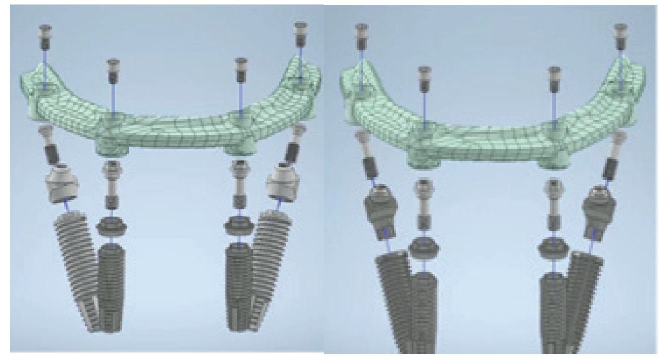
Fig. 1 Components of the All on 4 assembly: (**a**) bar of implant; (**b**) prosthetic - screw; anterior implant assembly: (**c**) fixture of implant, (**d**) abutment, and implant - screw; posterior implant assembly in the E-HC group: (**e**) fixture of implant, (**f**) abutment, and implant - screw; posterior implant assembly in the I-HC group: (**g**) fixture of implant, (**h**) abutment, and implant - screw.

measurement accuracy, vernier callipers and a digital microscope were used to measure every component, including bar of implants, MUAs, prosthesis screws, and implant screws. These model were then scanned using a three dimensional optical scanning system (AiconSmartScan-HE) to provide high-resolution images. Lastly, finite element analysis (FEA) software (ANSYS Workbench 2020 R1 and computer-aided design (CAD) software (Inventor2020) were used to construct the 3D models. Two sets of finite element models for the "All on 4 assembly" are displayed in Figure 2.

In order to replicate the human bone structure, the examined model was imported into a 50 mm × 30 mm × 40 mm bone block model using FEA software. The bone block model has a 3mm thickness outer layer that mirrored the cortical bone and a spongeous inner substance mimicked cancellous bone.

Finite element analysis

Tetrahedron elements (SOLID187), with 10 node elements with quadratic displacement, were used to mesh all components. It is high order 3D element that works well for irregular meshes. Furthermore, we employed various elements with sizes sizes, ranging



(a) (b)

Fig. 2 Finite element model in (**a**) E-HC group and (**b**) I-HC group.

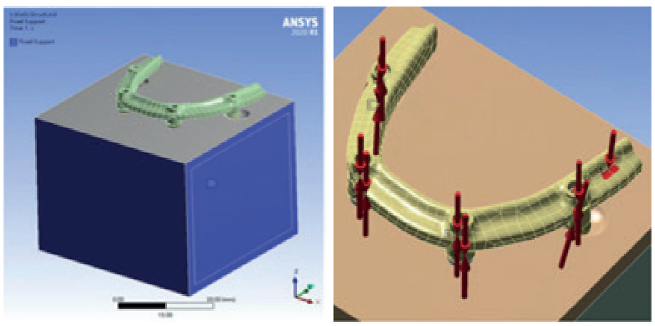
from minimum 0.08 to maximum 2.00 mm, in order to obtain accurate results. The E-HC and I-HC groups were similarly meshed with the same amount of pieces. E-HC group employed about 1,885,434 elements and 2,842,741 nodes, whereas I-HC group employed, 1,948,198 elements and 2,954,778 nodes.

Utilizing energy dispersive X ray spectroscopy (JSM-6360), the current study's materials, were confirmed. Furthermore, we made the assumption that all the included materials, and also bone had isotropic, homogeneous, and elastic properties for the purposes of our investigation. The material's mechanical characteristics utilised for the bone and All on 4 components were determined in earlier research and are shown in Table 1 [19–21] below.

Table 1 Mechanical properties of the materials used in the model.

Material	Young's Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)
Cortical bone	13.4	0.30	-
Cancellous bone	1.37	0.30	-
PureTitanium (Implant fixture)	115	0.35	680
Ti-6Al-4V alloy (Implant bar, Implant screw, Prosthetic screw, Screws, Abutments)	110	0.33	795

It was thought that the interface between the cancellous and cortical bones was bonded, permitting the main attention to be on the loading effects on the All on 4 assembly's components. It was believed that the bone implants interface was completely osseointegrated. As a result, the bone-implant interface was set to "bonded." We used a coefficient of friction of 0.3 to account for frictional cause inside each All on 4 model component. Applying a stable pillar to all surfaces of the bone block model (Figure 3a) allowed us to limit displacement in three directions to zero in the boundary conditions, except for the occlusal surface.



(a) (b)

Fig. 3 Boundaries and loading conditions of the models

(**a**) Bone block model's boundary condition fixed and supported on all non occlusal surfaces (**b**) Application of 190 N vertical force to the bar of implant. Bolt pretension with axial force on the prosthetic - screw and implant - screws .

With the calculation

T = KDF,

where T is tightening torque (N·m), K is torque coefficient , D is screw diameter (m), and F is reflects the axial force (N), we converted the Screw's tightening torque as the axial force on force application. Following the manufacturer's instructions, we tightened the prosthetic - screw by 0.1 N·m, the implant - screw's mesial surface by 0.35 N·m, and the implant - screw's distal surface by 0.15 N·m. We determined the corresponding axial force to be 192.01 N, 457.56 N, and 215.51 N, respectively, using these torques. Under loading circumstances, the bar of implant, positioned around 10 mm distal to the posterior implant's prosthetic - screw was subjected to a 190 N vertical force (Fig. 3b).

3. Statistical analysis

3.1 Descriptive statistics

Clinical features were summed up in the primary analysis as frequencies (N), percentages (%), measures of central tendency and variability. Chi-square tests and t-tests/ Mann-Whitney U tests were used for non parametric and parametric variables respectively. The biomechanical performance characteristics will be evaluated using multivariate analysis of variance (MANOVA).

3.2 Machine learning for predictive modeling

Predictive models will be developed with machine learning techniques like Random Forest and Support Vector Machines. These models will be validated using cross-validation methods like k-fold cross-validation, and measures like accuracy, precision, recall, and AUC-ROC will be used to assess how well they perform. Important biomarkers that aid in illness prediction will be found using feature importance analysis.

4. Results and discussion

Under identical loading conditions, both the groups showed the same findings relating distribution of stress values in the All on 4 assembly's posterior implants. In both groups, the prosthetic - screws had the greatest von Mises stress values, followed by the

MUAs, as Figure 4 illustrates.

According to the findings of the current research, MUAs and prosthetic - screws may denote the weak points on the posterior implant of the All on 4 assembly. Interestingly, these stress levels were near to but not higher than the Ti-6Al-4V alloy's yield strength, which is approx. 795 MPa. For the prosthetic - screws, the E-HC group's peak von Mises stress values were 699.00 MPa,

while the I-HC group's were 681.63 MPa. Second, bone consistently showed the lowest von Mises stress levels, with the E-HC group recording 99.91 MPa and the I-HC group recording 93.17 MPa. This result suggests that a significant amount of the stress was absorbed by the metallic parts of the All on 4 system, reducing the amount of stress that was transferred to the surrounding bone. Furthermore, the von Mises stress values on the bar of implant, prosthetic - screw, MUAs, and bone were comparable in the two groups; the E-HC group's value was slightly higher than the I-HC group's. In particular, the bar of implant, prosthetic - screw, MUAs, and bone all had von Mises stress peak values in the E-HC group that were 8.8%, 1.2%, 5.3%, and 6.2% greater than those in the I-HC group, respectively. Finally, there was a decline in the maximum von Mises stress values from

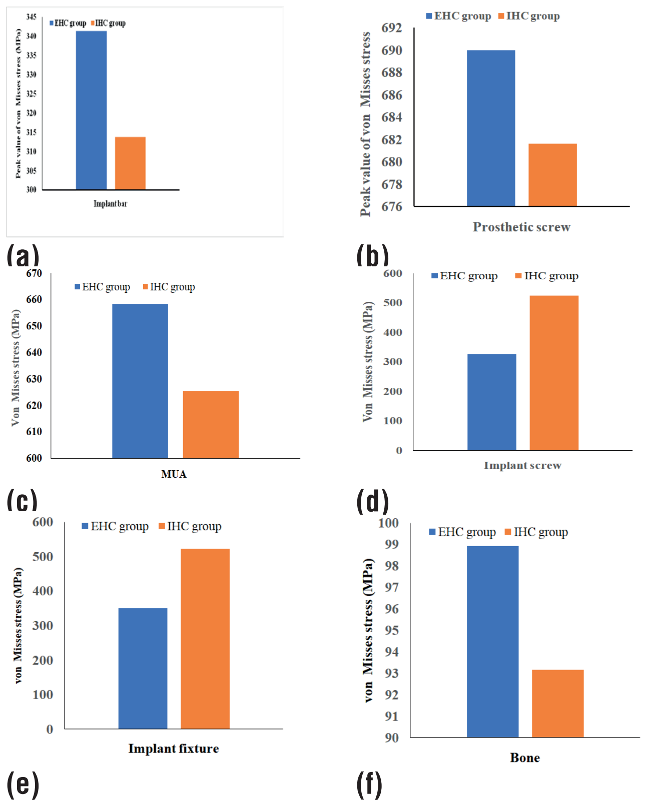


Fig. 4 Peak values of von Mises stress on implant's (a) bar, (b) prosthetic - screw, (c) MUA, (d) screw, (e) fixture, and (f) bone in the E-HC and I-HC groups

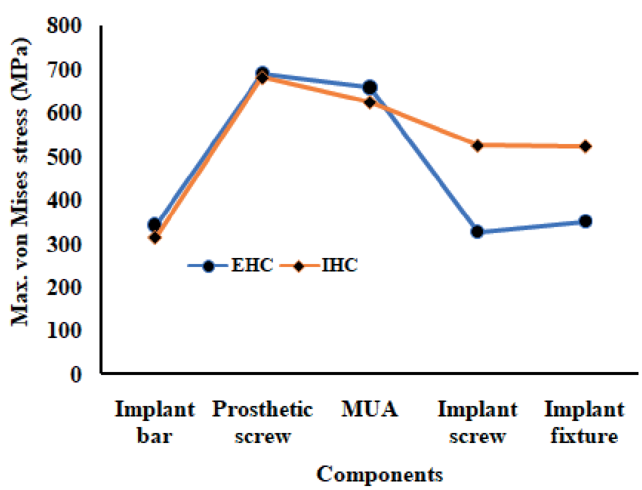


Fig. 5 Maximum von Mises stress on each component of the E-HC and I-HC groups.

Figure 5 illustrates that the maximum von Mises stress values for the implant - screws and fixture of implants in the two groups differed significantly. It is interesting to point out that the E-HC group's peak stress values for the fixture of implant and screw were obviously lower than those of the I-HC group. The von Mises stress values of the implant - screw in the E-HC group were 37.75% lower than those in the I-HC group.

Furthermore, von Mises stress values for the fixture of implants in the E-HC group were 33.03 percent lower than those in the I-HC group. These findings imply that there were variations in the two groups' stress distributions. The load transfer in the E-HC group was mostly concentrated on prosthetic - screws and MUAs, even though the stress was uniformly distributed with lower von Mises stress values on the bar of implant, implant - screw, and fixture of implant. However, in the I-HC group, the stress was more evenly distributed throughout the prosthetic - screw, MUAs, implant - screw, and fixture of implant.

The load transmission through each part of the 3D finite element model resulted in distinct patterns of stress distribution. In general, the load force tended to concentrate at locations where parts were connected. Von Mises stress levels on the bar of implant, prosthetic - screw, MUAs, and bone were comparable among the groups, as was previously mentioned. However, we found that the distal-lingual surface of the ring junction was where the bar of implant's largest stresses were found when we looked at the region of each group component where the greatest stress is concentrated. The third thread / the middle part of the prosthetic - screw, experienced the greatest strains. Similarly, the two groups had the highest forces on the surrounding bone in the cantilever region, which is located in the cervical 3rd of the fixture of implant. However, the E-HC and I-HC groups' peak stress values were located differently with respect to each other. In the E-HC group, the maximum stress was found on the innermost surface of the distal region of the thread, which attaches to the prosthetic - screw. In contrast, the I-HC group had the most stress at the junction with the fixture of implant.

Even though the von Mises stress magnitudes differed noticebly between the two groups, there were some similarities in the most stressed location for the implant - screws and fixtures. The first thread of implant - screw connecting to the MUAs, was the most tense. In all groups, the most stressed area was found to be the cervical portion of the fixture of implants, where they attach to the MUAs. In the E-HC group, this point was outside the first thread of the fixture of implant. Conversely, in the I-HC group, the greatest amount of tension was placed on the interior contact surface between the MUAs and the fixture of implant.

5. CONCLUSION

Within the constraints of the research, the following conclusions can be made in light of the results of this FEA study. When the mandibular All on 4 assembly's distal cantilever portion experiences an axial force:

1. Under the tested loading circumstances, both E-HCs and I-HCs exhibit clinical durability.

2. The prosthetic - screw and MUAs were the most strained areas in the E-HC and I-HC groups, suggesting that these parts may be the vulnerable spots on the posterior implant within the All on 4 assembly.

3. Compared to the I-HC group, the E-HC group's implant - screw and fixture of implant had peak stress values that were 37.75% and 33.03% lower, respectively.

4. It is crucial to optimize design of the implant especially with specific implant–abutment connections for preventing overload and the resulting clinical repercussions.

To confirm the results from the current FEA, more research is necessary.

Data availability statement

This study's supporting data available upon reasonable request.

Conflict of interests

No conflict of interest amongst the authors.

REFERENCES

[1] Ministry of Health and Welfare of Taiwan. [(accessed on 17 January 2018)]; Available online: https://dep.mohw.gov.tw/DOOH/lp-6553-124.html.

[2] Centers for Disease Control and Prevention. [(accessed on 25 September 2023)]; Available online: https://stacks.cdc.gov/view/cdc/82756/cdc_82756_DS1.pdf.

[3] Soboleva U., Rogovska I. Edentulous Patient Satisfaction with Conventional Complete Dentures. Medicina. 2022; 58:344. doi: 10.3390/medicina58030344. [DOI] [PMC free article] [PubMed] [Google Scholar]

[4] Li T., Hu K. Optimum selection of the dental implant diameter and length in the posterior mandible with poor bone quality—A 3D finite element analysis. Appl. Math. Model. 2011; 35:446–456. doi: 10.1016/j.apm.2010.07.008. [DOI] [Google Scholar]

[5] Malo P., Rangert B., Nobre M. "All-on-Four" immediate-function concept with Brånemark system implants for completely edentulous mandibles retrospective clinical study. Clin. Implant Dent. Relat. Res. 2003; 5:2–9. DOI: 10.1111/j.1708-8208.2003.tb00010.x. [DOI] [PubMed] [Google Scholar]

[6] Maló P., de Araújo Nobre M., Lopes A., Ferro A., Botto J. The All-on-4 treatment concept for the rehabilitation of the completely edentulous mandible: A longitudinal study with 10 to 18 years of follow-up. Clin. Implant Dent. Relat. Res. 2019; 21: 565–577. doi: 10.1111/cid.12769. [DOI] [PubMed] [Google Scholar]

[7] Chan M.H., Holmes C. Contemporary, 'All-on-4' Concept. Dent. Clin. N. Am. 2015;59: 421–470. doi: 10.1016/j.cden.2014.12.001. [DOI] [PubMed] [Google Scholar]

[8] Soto-Penaloza D., Zaragozí-Alonso R., Penarrocha-Diago M., Penarrocha-Diago M. The all-on-four treatment concept: Systematic review. J. Clin. Exp. Dent. 2017; 9:e474–e488. doi: 10.4317/jced.53613. [DOI] [PMC free article] [PubMed] [Google Scholar]

[9] Tsai MH, Lee CH, Wu AY, Lei YN, Chen HS, Wu YL. A Biomechanical Evaluation of Distal Tilting Implants in All-on-Four Rehabilitation with Mild Mandibular Resorption: A Finite Element Analysis Study. Materials (Basel). 2024 Nov 7;17(22):5435. doi: 10.3390/ma17225435. PMID: 39597258; PMCID: PMC11595311.

[10] Soboleva U, Rogovska I. Edentulous Patient Satisfaction with Conventional Complete Dentures. Medicina (Kaunas). 2022 Feb 24;58(3):344. doi: 10.3390/medicina58030344. PMID: 35334520; PMCID: PMC8953744.

[11] Abuhussein H., Pagni G., Rebaudi A., Wang H.L. The effect of thread pattern upon implant osseointegration. Clin. Oral Implants Res. 2010; 21: 129–136. DOI: 10.1111/j.1600-0501.2009.01800.x. [DOI] [PubMed] [Google Scholar]

[12] Tallarico M., Meloni S.M., Park C.-J., Zadrożny Ł., Scrascia R., Cicciù M. Implant Fracture: A Narrative Literature Review.

Prosthesis. 2021; 3:267–279. doi: 10.3390/prosthesis3040026. [DOI] [Google Scholar]

[13] Valvi, Nikita &Khalikar, Smita & Mahale, Kishor & Rajguru, Vilas & Mahajan, Sonali & Tandale, Ulhas. (2024). Evolving interfaces: A comprehensive review of implant-abutment connections. International Dental Journal of Student's Research. 12. 123-129. 10.18231/j.idjsr.2024.024.

[14] Maló, P., de Araújo Nobre, M., Lopes, A., Ferro, A., & Botto, J. (2019). The All-on-4 treatment concept for the rehabilitation of the completely edentulous mandible: a longitudinal study with 10 to 18 years of follow-up. Clinical implant dentistry and related research, 21(4), 565-577.

[15] Pera F., Menini M., Bagnasco F., Mussano F., Ambrogio G., Pesce P. Evaluation of internal and external hexagon connections in immediately loaded full-arch rehabilitations: A within-person randomized split-mouth controlled trial with a 3-year follow-up. Clin. Implant Dent. Relat. Res. 2021; 23:562–567. doi: 10.1111/cid.13029. [DOI] [PMC free article] [PubMed] [Google Scholar]

[16] Miyashita, M., Leepong, N., Vichitkunakorn, P. and Suttapreyasri, S. (2025), Impact of Cantilever Length on the Accuracy of Static CAIS in Posterior Distal Free-End Regions. Clin Implant Dent Relat Res, 27: e70020. https://doi.org/10.1111/cid.70020

[17] Tandon, Pranay& Chaudhary, Aditya & Punit, R & Khurana, Punit & Aggarwal, Dr & Kartika, N & Kumar,. (2024). Effect Of Different Implant Placement Protocols Along With Immediate Loading On Survivability And Peri- Implant Tissue Health -A Systematic Review. IOSR Journal of Dental and Medical Sciences. 23. 1-07. 10.9790/0853-2308060107.

[18] Şentürk, A., Akaltan, F. Biomechanical behavior of all-on-4 concept and alternative designs under different occlusal load configurations for completely edentulous mandible: a 3-D finite element analysis. *Odontology* 112, 1231–1247 (2024). https://doi.org/10.1007/s10266-024-00941-1

[19] Akca K., Iplikcioglu H. Finite element stress analysis of the influence of staggered versus straight placement of dental implants. Int. J. Oral Maxillofac. Implants. 2001; 16: 722–730. [PubMed] [Google Scholar]

[20] Teixeira E.R., Sato Y., Akagawa Y., Shindoi N. A comparative evaluation of mandibular finite element models with different lengths and elements for implant biomechanics. J. Oral Rehabil. 1998; 25: 299–303. DOI: 10.1111/j.1365-2842.1998.00244.x. [DOI] [PubMed] [Google Scholar]

[21] Pierrisnard L., Hure G., Barquins M., Chappard D. Two dental implants designed for immediate loading: A finite element analysis. Int. J. Oral Maxillofac. Implants. 2002;17: 353–362. [PubMed] [Google Scholar]