# A Biomechanical Finite Element Analysis of All-on-Four Concept using Short Implants in Maxilla

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## Abstract

Despite the advantages, The All-on-four concept has the disadvantage that the bone around the posterior (tilted) implant receives the highest pressure distribution. This study analyzed various implant-supported denture designs in the maxilla developed from the All-on-four concept using short implants as an alternative to the All-on-four concept.

This study uses the Finite Element Method. All implants were placed parallel to the axial axis. Design A (All-on-four) was the control design. Design B: eliminate the tilted implant in the posterior and place one 6 mm implant in each of the left and right permanent maxilla first molar regions. Design C: same as Design B but place one 6 mm implant in each of the left and right permanent maxilla second Premolar, and first Molar regions. Design D (All-on-short) same as Design C but uses short implants both anterior and posterior. Designs B, C, and D had no distal cantilever. The axial load of 80N and an oblique load of 50Nx3 were applied separately.

The simulation results showed that Design C has the lowest stress and Design B has the highest stress.

It can be concluded that biomechanically, short implants can be used to treat patients with complete edentulous.

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## Introduction

The All-on-four treatment concept was developed to maximize the use of residual bone in atrophied jaws. This technique has the advantage of allowing a complete and functional denture to be made immediately after insertion and avoiding regenerative procedures that would increase treatment costs and patient morbidity, as well as possible complications.[1] The All-on-four procedure uses four implants in the non-toothed jaw to support a temporary fixed complete denture, which can function immediately after insertion. The two most anterior implants are placed axially, while the two posterior implants are placed distally and tilted to avoid anatomically important structures (maxillary sinus and mandibular canal), minimizing cantilever length, and allowing a complete denture of up to 12 teeth to be made, thereby improving masticatory efficiency.[2,3]

Various studies[4,5] have shown that the highest-pressure distribution in the All-on-four system is in the bone around the most posterior implant, adjacent to the denture cantilever. The two implants in the anterior region showed a lighter pressure distribution than those in the posterior region.[4,5]

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Previous studies have shown that implant length is not associated with the overall survival rate of an implant restoration. Clinical and laboratory studies have shown that short implants have proven long-term survival and are comparable to long implants.[5,6,7] Extra-short implants with a length of 6 mm or shorter have a high success rate. These implants have a high success rate especially when splinted compared to unsplinted.[8] The study by Lombardo et al.[9] proved that short and extra-short implants have a high success rate in single restorations of maxillary Premolars and Molars.[9]

Most existing studies on short or extra-short implants have been conducted on single implant restorations or implant-retained partial dentures, and it is rare to find research data on short implants in complete dentures, even though these short implants provide solutions in certain cases.[10]

## Materials and methods

The first step in this study was to digitally create a 3-dimensional (3D) model of the sample. The 3D models of the implants, abutments, and prosthetic components were created by drawing using Solidwork software. The 3D modeling of the implant was made regarding a clinically used product (Astra Tech Implant System EV, Dentsply Sirona Implants), with sizes of 15 mm length, 4.2 mm diameter; 11 mm length, 4.2 mm diameter; and 6 mm length, 4.2 mm diameter. The design of the bar substructure was made by simulating the substructure of a fixed complete denture with the assumption of replacing 12 teeth from the first Molar (tooth number 3) to the first Molar ( tooth number 14) of the opposite contralateral segment.

A three-dimensional geometric model of the maxilla was created by segmenting a copy of the Cone Beam Computed Tomography 3-D (CBCT-3D) file at the Bandung Institute of Technology, and then the results were processed using 3D Slicer and Solidworks software (Solidworks Corp., Dassault Systèmes) to produce a virtual three-dimensional solid model of the maxilla.[11] This virtual maxilla model also simulated the bone structure consisting of cancellous bone surrounded by cortical bone. The cortical bone tissue was modeled after the D3 and D4 bone types for the maxilla according to the Lekholm and Zarb Classification.[12] Each finished model was then assembled using Solidworks software to resemble an implant-supported complete denture according to the All-on-four concept along with design variations following the design to be studied (Figure 1).

The parameters varied in this study were the location, length, and number of implants. All implants were upright parallel to the axial axis. Design A: (All-on-four) was the control design. Design B: two 10 mm implants in the anterior region, and one 6 mm implant in each of the left and right first Molar regions. Design C: two 10 mm implants in the anterior region, one 6 mm implant in each of the left and right second Premolar (tooth number 4 and 13), and first Molar regions. Design D: two 6 mm implants in the anterior region, one 6 mm implant in each second Premolar, first Molar left and right regions. Since design D uses short implants in the entire region, it is also known as the All-on-short design. Designs B, C, and D had no distal cantilever in the maxilla.

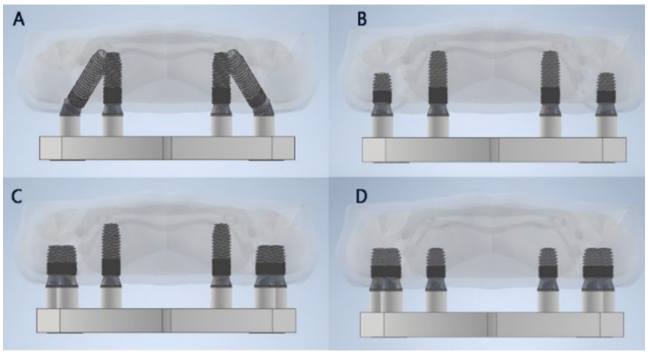


**Figure 1.** Maxillary Design Variations.

The next step is to simulate the loading on the substructure including a load of 80N at the point representing the middle of the maxillary first Molar, with the axial loading direction (in the direction of the vertical axis of the tooth) and a loading of 50Nx3 which is divided into 3 points of 50 N each at the point representing the middle of the first Premolar, second Premolar, and maxillary first molar, with the oblique loading direction forming an angle of 75° to the horizontal plane.

To perform the loading simulation, the bone implant assembly was entered into Abaqus and several parts were set up so that the loading simulation could be run. Important things that must be set up are the material used, mesh, boundary conditions, contact between components, and loading. The contact between components is set in the interactions module with constraints in the form of a tie for each contact that occurs.

The material types and properties used in this modeling can be seen in Table 1. The abutment, abutment screw, and implant body are made of the same material, titanium. The loading simulation results obtained are analyzed and presented in the form of tables and diagrams.

| Materials | Young Modulus (MPa) | Poisson Ratio (v) | Reference |
|---|---|---|---|
| Cortical bone | 13.000 | 0.30 | Carter and Spengler[14] |
| Cancelous bone (D1) | 9.500 | 0.30 | Rho et al.[15] |
| Cancelous bone (D2) | 5.500 | 0.30 | Rho et al.[15] |
| Cancelous bone (D3) | 1.600 | 0.30 | Rho et al.[15] |
| Cancelous bone (D4) | 690 | 0.30 | Rho et al.[15] |
| Titanium | 110.000 | 0.35 | Patra et al.[16] |
| CoCr framework | 218.000 | 0.33 | Bhering et al.[1] |

**Table 1.** Material Parameters of the Research Model.[13]

## Results

The results of the loading simulation on the maxilla are the maximum and minimum Principal Stress values, which show the highest values of compression and tensile on the bone around the implant due to the loading that has been carried out. The results of the loading simulation on the maxilla are shown in Tables 2 and 3, and Figure 2.

| Design Variations | Highest Maximum Principal Stress 80 N Load (in MPa) | Highest minimum Principal Stress 80 N Load (in MPa) |
|---|---|---|
| A | 68,58 | 50,08 |
| B | 87,08 | 64,29 |
| C | 39,83 | 43 |
| D | 42,44 | 67,4 |

**Table 2.** Simulation results of loading on the maxilla with a load of 80 N in the axial direction.

| Design Variations | Highest Maximum Principal Stress 50 N x3 Load (in MPa) | Highest Minimum Principal Stress 50 N x3 Load (in MPa) |
|---|---|---|
| A | 89,55 | 74,15 |
| B | 129,2 | 90,08 |
| C | 50,74 | 58,29 |
| D | 50,81 | 58,31 |

**Table 3.** Simulation results of loading on the maxilla with a load of 50 N x3 in the oblique direction.

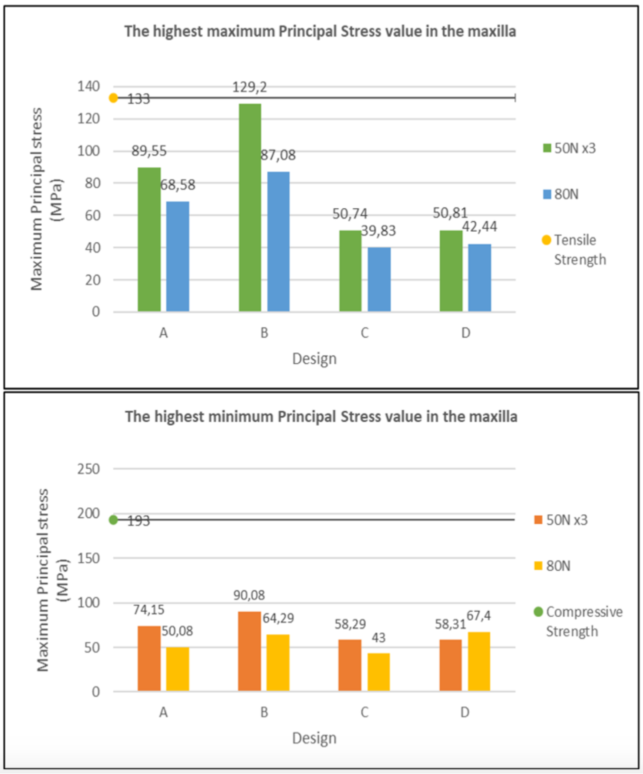


**Figure 2.** The highest maximum and minimum Principal Stress value in the maxilla with 80 N and 50 N load x3.

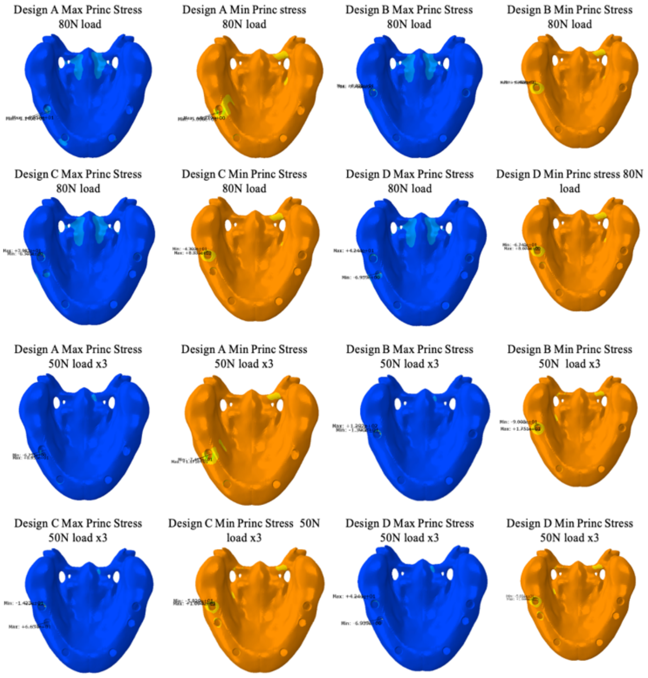
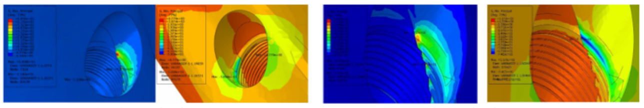
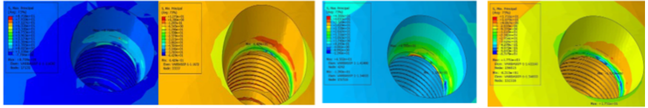


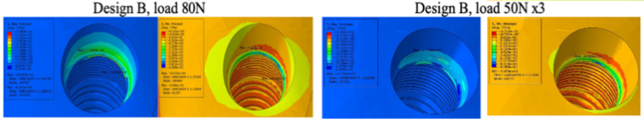
**Figure 3.** Maximum and minimum principal stress locations for each design.

From Tables 1 and 2, at 80 N axial loading, Design C produces the maximum principal stress and the smallest minimum principal stress in the bone around the implant. Design D, which used All-on-short implants, produced maximum principal stress and minimum principal stress values that were greater than those of Design C but still lower than those of Design A (All-on-four) and B. In general, Design B resulted in the highest values of bone stress around the implant. The strategy of using one short implant at each end of the distal arm to eliminate the distal cantilever did not sufficiently reduce the maximum and minimum principal stress values received by the bone around the implant.

The location of the bone around the implant that receives the most stress and the location of the critical area of each design can be seen in Figures 3 and 4. The results of this Finite Element Method analysis have no variance, so no statistical analysis is required.[5]


Design A, load 80N
Design A, load 50N x3N


Design B, load 80N
Design B, load 50N x3


Design C, load 80N
Design C, load 50N x3

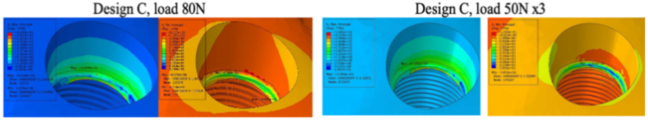


**Figure 4.** Location of critical areas of each design.

## Discussion

Based on the simulation results on the maxilla, when compared with Design A (All-on-four), which is considered the control design, Design B produces higher values of maximum and minimum principal stress than Design A. Design C and D simulations, on the other hand, produced lower maximum and minimum principal stress values than Design A (All-on-four). It is likely to be mainly influenced by the bone density at the site where an implant is placed. The posterior of the maxilla is the area with the lowest bone density, so one short implant was insufficient to withstand the simulated load in this study, requiring at least two short implants at each distal end of the cantilever to reduce the stress in the bone around the implant.

Bidez et al.[18] stated that implant-supported prostheses should avoid designs with cantilevered distal arms because these cantilevers would place a greater load on the bone around the most distal implant, and it is feared that the load would be excessive, causing bone resorption.[18] The placement configuration of Design B attempts to eliminate the cantilever arm in Design A, while still maintaining the overall number of implants used, which is 4 implants. However, the simulation results showed higher stress distribution values than Design A.

This result may be due to the difference in density of the most distal implant placement location between Design A and Design B. In Design A, the most distal implant with a length of 15 mm was placed in regions 13 and 4 tilted medially 30°. This configuration of placement location, size, and angle of inclination made the implant body location mostly in bone with higher density than in Design B. In Design B, the two 15 mm tilted long implants used in Design A were removed and replaced with one short 6 mm implant at both ends of the distal cantilever. Elimination of the two distal cantilevers by placing short implants would result in both short implants being in low-density bone, which would be unfavorable for pressure distribution to the bone around the implants.

Concerning the explanation above, bone density is generally divided into 4 classifications, namely D1, D2, D3, and D4. D1 type bone is usually located in the anterior area of the mandible, D2 in the posterior of the mandible, D3 in the anterior of the maxilla, and D4 in the posterior of the maxilla. D4 is the lowest-density bone type and D1 is the highest-density bone.[19] Thus, for Design B in the maxilla, the short implant used is in the D4 bone type, which is low-density bone.

The results of the study by Premnath et al.20 showed that decreased bone density leads to increased stress levels around the implant neck, especially for threaded implants.[20] Sevimay et al.21 who utilized the Finite Element Method to analyze the effect of different bone densities on stress distribution, concluded that higher stress magnitudes were seen in D3 and D4 bone types, which have weaker bone trabecular structures and less resistance to deformation than D1 and D2 bone qualities.[21]

In posterior regions with low-density bone, the strain on the bone surrounding the short implant will increase, exceeding its strain threshold value and showing a tendency for resorption. In situations where short implants are required in the posterior region, the number of short implants should be increased.[22,23] This can be seen in the simulation results of Design C and D when compared to Design B.

In Designs C and D of the maxilla, the maximum and minimum principal stress values of both designs were lower than those of Designs A and B of the maxilla. In contrast to Design B, Design C and D added 2 short implants each to the distal cantilever end, a development of Design B that aimed to eliminate the cantilevered distal arm. Changing the number of short implants from 1 to 2 and then rigidly joining them together (splinting) is expected to provide better biomechanical effects. The meta-analysis study conducted by Papaspyridakos et al.[24] recommended splinting multiple short implants as a single unit, based on data from most of the journals included in their study which showed that splinting multiple short implants provided better occlusal force distribution.[24]

Designs C and D have a slight difference in the implant length configuration in the anterior region. In Design C, an 11 mm long implant is used, while Design D uses a short 6 mm implant. Although some studies have shown that the highest bone stress occurs in the bone around the most distal implant, and the stress in the bone around the anterior implant is lower, this study shows that the anterior implant length still influences reducing the stress in the bone around the posterior implant. In this study, it was observed that Design D gave higher maximum and minimum Principal Stress values than the simulation results of Design C. This indicates that the longer the length of the implant in the anterior, the better the stress around the implant in the posterior. This suggests that the longer the implant size in the anterior segment, the lower the stress distribution in the bone around the short implant in the posterior segment. In the 80 N axial load simulation in the maxilla, all maximum and minimum Principal Stress values were in the bone around the most distal implant group. In the 50N x3 N load simulation in the oblique direction in the maxilla, Design C showed the highest maximum Principal Stress location in the bone area around the second Premolar region implant, while for Design A, B, and D the maximum Principal Stress was at the most distal implant. The minimum Principal Stress for the simulated 50N x3 N maxillary load was all at the bone around the most distal implant.

The area/location of implant placement is an important aspect to consider. The likelihood of failure is higher when implants are placed in low-density bone, such as in the posterior maxilla.[25] However, there is no consensus regarding the survival rate of short implants in the posterior maxilla and mandible.[26] Some authors show low success rates, while others show high success rates for short implants.[27]

A systematic review and meta-analysis by Lemos et al.[27] concluded that short implants show similar rates of marginal bone loss, prosthesis failure, and complication rates as standard implants. As such, the use of short implants for the posterior area is considered a predictable treatment option, particularly in cases that require complementary surgical procedures. However, short implants less than 8 mm in length (4-7 mm) should be used with caution as they pose a greater risk of implant failure when compared to standard implants.[27]

From the simulation results of all designs in the maxilla, Design C produced the lowest bone stress distribution compared to the other designs. Thus, maintaining the use of standard-size implants for the anterior segment of the maxilla contributes significantly to lowering the stress on the bone around the posterior implants, which is expected to increase the long-term success of an implant-supported complete denture treatment in the maxilla. However, all maximum and minimum Principal Stress values in this maxillary simulation are still below the the ultimate strength of the bone. For information, the highest bone tensile strength value is 133 MPa and the highest bone compressive strength value is 193 MPa.[28,29]

## Conclusions

This study concludes that biomechanically, short implants can be used for the treatment of patients with complete tooth loss in both the maxilla and mandible. The use of short implants can be combined with standard-length implants or all-on-short implants. Eliminating the distal cantilever arm in the All-on-four design using two short implants has been shown to reduce stress in the bone around the implant. The best design in this maxillary study was Design C.

## Declaration of Interest

The authors report no conflict of interest.

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