PEDRO GOMES JUNQUEIRA MENDES

ANÁLISE BIOMECÂNICA DA INFLUÊNCIA DO COMPRIMENTO E ANGULAÇÃO EM IMPLANTES DISTAIS DE REABILITAÇÕES *ALL-ON-FOUR* EM MAXILAS: UM ESTUDO DE ANÁLISE DE ELEMENTOS FINITOS

Biomechanical Analysis of the Influence of Length and Angulation in Distal Implants of All-on-Four Rehabilitations in Maxillae: A Finite Element Analysis Study

Dissertação apresentada à Faculdade de Odontologia da Universidade Federal de Uberlândia, como requisito parcial para obtenção do Título de Mestre em Odontologia na Área de Clínica Odontológica Integrada.

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Orientador: Prof. Dr. Guilherme José Pimentel Lopes de Oliveira

Banca de Defesa

Profª. Drª. Germana de Villa Camargos

Profº.Drº. Humberto Osvaldo Schwartz Filho

Prof. Dr. Guilherme José Pimentel Lopes de Oliveira

Uberlândia, 2025

ATA DE DEFESA - PÓS-GRADUAÇÃO

Programa de Pós-Graduação em:	Odontologia				
Defesa de:	Dissertação de Mestrado Acadêmico, 465, PPGODONTO				
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Título do Trabalho:	Análise biomecânica da influência do comprimento de implante e angulação em implantes distais de reabilitações all-on-four em maxilas: um estudo de análise de elementos finitos				
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Iniciando os trabalhos a presidente da mesa, Dr. Guilherme José Pimentel Lopes de Oliveira, apresentou a Comissão Examinadora e o candidato(a), agradeceu a presença do público, e concedeu ao Discente a palavra para a exposição do seu trabalho. A duração da apresentação do Discente e o tempo de arguição e resposta foram conforme as normas do Programa.

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Aprovado.

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SUMÁRIO

RESUMO

O objetivo desta dissertação foi avaliar a influência biomecânica de diferentes comprimentos e angulações de implantes distais em reabilitações do tipo All-on-Four na maxila. Foi avaliada a influência biomecânica da variação na angulação dos implantes distais, no comprimento de implante, no design de implante, na força aplicada sobre os modelos e nas condições clínicas simulando carga imediata e carga tardia, totalizando 64 modelos de elementos finitos simulados. Foi avaliado o pico de deformação equivalente, o volume ósseo submetido a microdeformações superiores a 4000 $\mu\varepsilon$ e o pico de tensão equivalente (von Mises) no parafuso do intermediário (abutment). Todos os dados foram analisados por meio do teste ANCOVA, complementado pelo teste de Tukey, adotando-se nível de significância de 5% ($p < 0,05$). Observou-se que o aumento da força aplicada e angulações superiores a 45º resultaram em maiores picos de deformação e volumes ósseos acima do limiar fisiológico, com concentração de tensões na região distal do pescoço dos implantes angulados, fator que pode aumentar o risco de perda óssea marginal. Para implantes angulados a 45º, o aumento do comprimento apresentou efeito limitado, enquanto o design do implante demonstrou maior influência na distribuição das deformações, especialmente em comprimentos maiores.

Palavras-chave: Implantes dentários, biomecânica, análise de elementos finitos.

ABSTRACT

The objective of this dissertation was to evaluate the biomechanical influence of different lengths and angulations of distal implants in All-on-Four maxillary rehabilitations. The biomechanical impact of variations in distal implant angulation, implant length, implant design, applied force on the models, and clinical conditions simulating immediate and delayed loading was assessed, totaling 64 simulated finite element models. The analysis included peak equivalent strain, the volume of bone subjected to microstrains exceeding 4000 με, and the peak equivalent stress (von Mises) on the abutment screw. All data were analyzed using ANCOVA, followed by Tukey's post hoc test, with a significance level set at 5% ($p < 0.05$). It was observed that increased applied force and angulations greater than 45º resulted in higher strain peaks and bone volumes above the physiological threshold, with stress concentration in the distal region of the angled implant necks, a factor that may increase the risk of marginal bone loss. For implants angled at 45º, increasing the length had a limited effect, while implant design showed a greater influence on strain distribution, especially at longer lengths.

KEYWORDS: Dental implants, Biomechanics, Finite Element Analysis

INTRODUÇÃO

O uso de implantes para a reabilitação de dentes perdidos tem apresentado boa previsibilidade desde o advento dos implantes osseointegráveis de Brånemark, especialmente em casos de reabilitação total da mandíbula e maxila com próteses implanto-suportadas (Menini et al., 2019). Para o sucesso do procedimento cirúrgico, entretanto, é necessária uma disponibilidade óssea mínima, a fim de permitir a instalação dos implantes sem intercorrências, como falha na osseointegração ou risco de comprometimento de estruturas anatômicas nobres (Maló et al., 2005). Todavia, o processo de reabsorção óssea nas regiões mandibular e maxilar é comum e esperado, sendo influenciado pelo tempo de edentulismo, podendo alcançar graus avançados de atrofia óssea (Fonteyne et al., 2021).

Essa limitação óssea pode inviabilizar a instalação de implantes, o que levou ao desenvolvimento e ampla utilização de técnicas de regeneração óssea, com o objetivo de recuperar o volume perdido, tanto em altura quanto em espessura (Shah et al., 2022). Apesar dos bons resultados clínicos obtidos com as técnicas de enxertia, seu uso é limitado pela quantidade de osso autógeno disponível, podendo também aumentar a morbidade para o paciente (Nkenke & Neukam, 2014). Além disso, condições sistêmicas podem representar fatores limitantes (Baihaqi et al., 2022), e estudos indicam que a osseointegração em áreas enxertadas apresenta qualidade inferior em comparação ao osso nativo (Lima et al., 2022; Quiroz et al., 2022).

Com o intuito de superar essas limitações, foi proposta a técnica "All-on-Four", que utiliza apenas quatro implantes para reabilitações totais, sendo dois deles inclinados distalmente para reduzir o cantiléver protético e evitar estruturas anatômicas críticas (Maló et al., 2005). Atualmente, essa técnica está bem estabelecida, com estudos de acompanhamento de 3, 4 até 17 anos, demonstrando taxas de sucesso que variam entre 94% e 99% para diferentes comprimentos de implantes distais (Uesugi et al., 2023; Yang et al., 2023).

Com o objetivo de aumentar a previsibilidade dos tratamentos reabilitadores com implantes dentários, novas possibilidades protéticas, variações de técnica cirúrgica e o desenvolvimento de superfícies e geometrias de implantes têm sido introduzidas na implantodontia (González-Valls et al., 2021). Dentre as soluções protéticas, destaca-se o uso de intermediários (abutments) angulados, permitindo a compensação de inclinações dos implantes, inclusive em ângulos superiores a 30º, como componentes de 45º e até 60º (Lopes et al., 2021). No entanto, o comportamento biomecânico desses implantes em grandes angulações ainda não é totalmente compreendido, especialmente quanto ao seu impacto na perda óssea marginal em reabilitações tipo *all-on-four* (Cortes-Breton Brinkmann et al., 2021; Tezerisener et al., 2024).

Sabe-se que a variação no design dos implantes pode alterar seu desempenho biomecânico e a distribuição de tensões no osso, podendo influenciar a longevidade do tratamento (Pala et al., 2024). Modificações na geometria do pescoço do implante, por exemplo, podem impactar significativamente a distribuição de tensões, sendo um fator importante na previsibilidade da perda óssea marginal (Dávila et al., 2019). Da mesma forma, o passo e a angulação da rosca influenciam o comportamento biomecânico, podendo aumentar ou reduzir tensões e deformações, afetando a estabilidade do implante e a distribuição de cargas no osso (Niroomand & Arabbeiki, 2020; Oswal et al., 2016).

No que se refere ao comprimento dos implantes, observa-se, de modo geral, que o aumento do comprimento tende a reduzir as tensões tanto no osso trabecular quanto no cortical (Falcinelli et al., 2023; Robau-Porrua et al., 2020) e em osso cortical (Robau-Porrua et al., 2020). Contudo, é importante destacar que esses achados derivam majoritariamente de estudos com implantes posicionados axialmente, havendo escassez de pesquisas que avaliem o efeito do comprimento em implantes inclinados (Baggi et al., 2008).

O método de análise de elementos finitos (FEA) é uma técnica numérica amplamente utilizada para analisar e simular fenômenos físicos por meio de modelos matemáticos, permitindo compreender e quantificar comportamentos estruturais, estresse mecânico, transporte térmico e até o crescimento de células biológicas (Falcinelli et al., 2023). Essa abordagem tem sido aplicada principalmente no desenvolvimento de produtos, com o objetivo de reduzir a necessidade de protótipos físicos e otimizar componentes de forma eficiente e econômica (Falcinelli et al., 2023). Na odontologia, a FEA mostra-se especialmente útil para estudar sistemas biomecânicos complexos, cuja investigação direta, seja in vivo ou in vitro, apresenta dificuldades (Falcinelli et al., 2023). Ele possibilita prever a resposta mecânica dos tecidos em diferentes condições de estímulo, tanto em situações saudáveis quanto patológicas, além de avaliar alterações estruturais. Dessa forma, a FEA se consolida como uma ferramenta viável e estratégica, oferecendo uma alternativa mais econômica, tanto financeiramente quanto biologicamente, para a condução de estudos em implantodontia (Falcinelli et al., 2023).

Revisões sistemáticas recentes destacam a importância de se investigar a influência de diferentes graus de inclinação dos implantes sobre a perda óssea marginal (Cortes-Breton Brinkmann et al., 2021), além da crescente demanda por estudos por elementos finitos que simulem com maior fidelidade as condições clínicas reais, por meio da utilização de geometrias anatômicas detalhadas (Falcinelli et al., 2023). Apenas um estudo de elementos finitos foi identificado na literatura avaliando conjuntamente a variação na angulação, comprimento e número de implantes (Gumrukcu & Korkmaz, 2018). Isso reforça a necessidade de estudos que explorem modelos mais representativos da realidade clínica, considerando a complexidade anatômica óssea e as interações entre osso e implante, tanto em cenários de carga imediata quanto tardia, abarcando as principais situações clínicas associadas à técnica *all-on-four*.

OBJETIVOS

Objetivo Geral

O objetivo dessa dissertação foi o de avaliar a influência biomecânica de diferentes comprimentos e angulações de implantes distais para reabilitações *all-on-four* em maxila.

Objetivos Específicos

1. Avaliar por meio da análise de elementos finitos a influência de diferentes angulações de implantes distais (30, 45 e 60º) com seus respectivos pilares angulados no comportamento biomecânico da maxila na reabilitação de *all-on-four*.
2. Avaliar por meio da análise de elementos finitos a influência do comprimento e do design (rosca invertida e rosca quadrada) em implantes distais (10, 13, 15, 18 e 22mm) angulados a 45º no comportamento biomecânico da maxila na reabilitação *all-on-four*.

1. CAPÍTULO 1

ARTIGO 1

O efeito de diferentes angulações de implantes distais no protocolo all-on-four maxilar - Análise por elementos finitos baseada em tomografia computadorizada específica do paciente.

The effect of different distal implant angulations in the maxillary all-on-four protocol - Patient specific CT-based finite element analysis

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Original Paper: The effect of different distal implant angulations in the maxillary all-on-four protocol - Patient specific CT-based finite element analysis

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Abstract

Purpose: The aim of this study evaluate the influence of different angulations of distal implants and their respective abutments on the biomechanical behavior in the rehabilitation of edentulous maxillae using the all-on-four technique. ***Material and Methods:*** Twenty-four finite element analysis (FEA) models were generated from a patient's edentulous maxilla (twelve in an immediately loading condition and twelve in a late loading condition). The applied loading forces during the FEA simulations were 440N and 550N. The distal implants presented the following variation: angulation (30, 45 and 60 degrees); length (10mm and 13mm). Peak equivalent strain (EQV strain) in the bone, bone volume above 4000με and peak equivalent von Mises stress (EQV stress) in the abutment screw were assessed. Data were collected and analyzed using ANCOVA complemented by Tukey with a significance level of 5% ($p < 0.05$). ***Results:*** It was observed that the greater angulations of the implants (45 and 60 degrees) and forces applied increased the Peak EQV Strain and the amount of bone with more than 4000μƐ in the region at the top of the bone crest associated with the implant. Increasing angulation (45 and 60 degrees) resulted in an increase in peak equivalent von Mises stress in the abutment screw. ***Conclusions:*** This study showed that increased angulantion of distal implants (45° and 60°) resulted in higher stress and strain in the peri-implant bone and implant components compared to lower angulation (30°), and implant length (10 mm vs 13 mm) had no significant effect on stress or strain distribution in the peri-implant bone or implant system.

Keywords: Dental implants, Biomechanics, Finite Element Analysis.

Introduction

The long-term success of the all-on-four technique in the maxilla is well-documented in the literature (Cannizzaro et al., 2018; Uesugi et al., 2023). This technique allows the rehabilitation of maxilla without the need for bone regeneration procedures by avoiding sinus areas by tilting the distal implants in most cases. This four-implant distribution is shown to be successful with studies showing survival rates of 97.4% in follow-ups of over 17 years (Uesugi et al. (2023).

The idea of tilting the distal implants in the all-on-four technique in the maxilla is to avoid anatomical structures, such as the maxillary sinus, and to reduce the prosthetic cantilever, which contributes to greater prosthetic stability. This angulation is applied only to the extent necessary to ensure safe implant placement. In this context, new prosthetic solutions are being introduced to support greater angulations for the rehabilitation of tilted implants, with components featuring commonly known angulations (17º, 30º, and 45º in most cases). Some companies even offer components with higher angulations, such as 60º abutments, which have been described in the context of rehabilitations of zygomatic implants (Lopes et al., 2021). Thus, the ability to work with greater angulations offers more options for patient rehabilitation and helps avoid more invasive procedures. However, despite the advantages of using greater angulations, biomechanical evaluations of full-arch rehabilitations have shown that the number of supporting implants plays a crucial role in load distribution, and tilting the implants may lead to increased accumulation of peri-implant stress and strain (Gumrukcu & Korkmaz, 2018).

Finite element analysis (FEA) evaluating different configurations of all-on-four has shown that increasing posterior implants angulation of 30º to 45º degrees may lead to increase in stress around these implants (Tezerisener et al., 2024). This may lead to accumulation that exceeds the bone's tolerance and may result in bone resorption (Duyck et al., 2001). However, the reporting of the influence of the degree of angulation of the tilted implants has on implant survival/success rate, marginal bone loss and biomechanical complications is poorly explored (Cortes-Breton Brinkmann et al., 2021). A recent systematic reviews show the need to assess the influence of different degrees of implant angulation on marginal bone loss (Cortes-Breton Brinkmann et al., 2021). Another review study also highlights the need for further finite element studies with clinical conditions closer to reality, using the total geometry of the maxillary bone (Falcinelli et al., 2023). To the authors knowledge, there is currently no study that evaluates the influence of different implant angulations in edentulous maxilla with a total specific maxillary finite elements model and associated with complex implant/ components contact configuration.

Thus, the primary objective of this study was to evaluate the influence of different angulations of distal implants and their respective abutments on the biomechanical behavior in the rehabilitation of edentulous maxillae using the all-on-four technique. The underlying hypothesis was that increasing the implant angulation would lead to higher levels of stress in the implant components and greater strain in the surrounding bone tissue, potentially compromising the biomechanical performance of the rehabilitation.

Materials and Methods

The present finite element simulation of an edentulous maxilla evaluated the all-on-four approach with distal implants in three different angulations (30, 45, and 60 degrees), two different lengths (10mm and 13 mm), and two different load boundary conditions (550 N and 660 N) for both immediate and delayed loading protocols.

The tomography was obtained from a patient included in another study that was approved by the Research Ethics Committee of the School of Dentistry of University Center of Triangulo - UNITRI (CAAE: 68368622.0.0000.5565). The computer tomography (CT) image of a totally edentulous patient was taken using cone beam computed tomographic scanning (Morita F 150 model X800; Morita corporation, Osaka, Japan) with the median sagittal plane perpendicular to the horizontal plane and the occlusal plane parallel to the horizontal plane. Voxel dimensions were 0.080 mm with 40x40 cm of field of view (FOV). The images were exported using the Digital Imaging and Communication in Medicine file format (DICOM). Bone segmentation and reconstruction of the maxillae geometry were accomplished in interactive medical imaging software (21.0 Mimics, Materialise, Haasrode, Belgium). The 3D solid models of computer-aided design (CAD) of commercially available implants of 3.8 mm in diameter and 10 and 13 mm in length (Epikut S®, S.I.N. - Implant system, São Paulo, Brazil), and the components (abutments, abutment screws, bar retaining screws, and titanium cylinders) were provided by the manufacture (S.I.N. - Implant system, São Paulo, Brazil) (Figure 2A). The solid models of the abutments with angles of 30, 45, and 60 degrees defined the different tilts of the distal implants. The framework beam (i.e., bar), shaped like a horseshoe and measuring 3.3 mm high and 1.6 mm thick to match the maxillae, along with the prosthesis, was created using CAD software (Exocad, Align Technology, Germany). Cantilevers of 13 mm from the most distal implant centers have been designed on both sides of the prosthetic device.

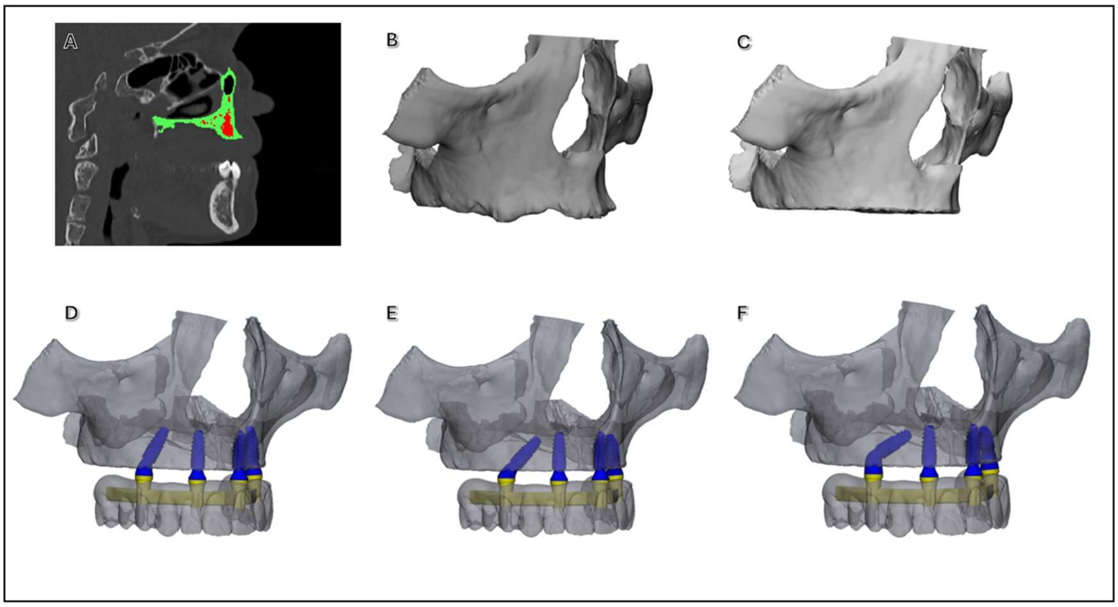


Figure 1. A) Maxillary bone segmentation. B) 3D reconstruction of the maxillary bone model. C) 3D bone model after the osteotomy. D) All-on-four model with 10 mm 30-degree tilted distal implants. E) All-on-four model with with 10 mm 45-degree tilted distal implants. F) All-on-four model with 10 mm 60-degree tilted distal implants.

Distal implant platforms remained at the same place, varying only the implant inclinations and the angulated abutments. The anterior implants were the same for all models (Figure 1). The components were aligned to the implants following the manufacturer's instructions (Figure 2B). No simplifications have been made in implant and components features (i.e. threads). The implants were numbered from 1 to 4, from the distal right side to the distal left side. The prosthesis and bar were aligned with the cylinders, and were glued by means of Boolean operation. All implants and components (i.e. abutments, abutment screws and bar retaining screws) interfaces were simulated as frictional contact (Coulomb frictional interface), adopting a frictional coefficient of μ=0.5 with a friccional coefficient. This configuration allows minor displacements between components without interpenetration of the meshes, resulting in pressure and tangential forces (friction) without tension. For immediate loading simulations frictional coefficient of μ=0.3 have been implemented in bone to implant interfaces. For delayed loading simulations (i.e. after implant osseointegration), bone to implant interface have been considered as glued.

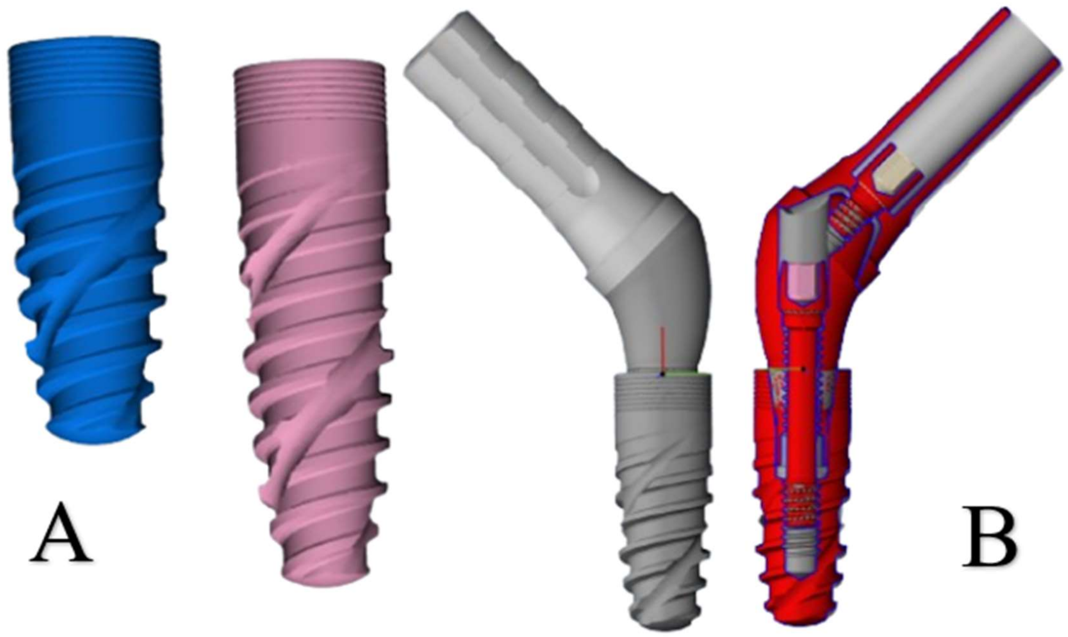


Figure 2. A) 10 mm and 13 mm implant models, respectively. B) Implant, abutment, abutment screw and bar retaining screw models.

The CAD models of bone, implants, abutments, abutment screws, bars, bar retaining screws, and the prosthesis were meshed separately in Patran (2010, MSC.Sfotware, Gouda, Nederlands), and whenever necessary, corrections, adjustments and refinements in the STLs were made in 3Matic® (14.0 Materialise, Hassrode, Belgium). Different element sizes were used to faithfully represent each CAD geometry. Implant osteotomies have been obtained by means of Boolean subtraction of implants from bone models.

Tetrahedral elements were used to construct solid finite element models, with a total of 927,992 to 979,395 elements and 214,607 to 226,191 nodes, depending on distal implants length. The bone solid mesh comprised the entire volume inside the outer bone surface. The threshold of CT image grey values was used to apply different material properties (i.e. Young's modulus and Poisson's ratio), discriminating each cortical and bone marrow (Figure 1).

The material properties (Young's modulus and Poisson's ratio) used in the present study were adopted from relevant literature (Gumrukcu & Korkmaz, 2018; Sousa et al., 2016) and are described in table 1. Second-order effects of tightening of abutments and screw preload in abutment screws and bar retaining screws were not considered in the present study.

Table 1: Mechanical properties of simulated materials.

Properties	Materials			
	Titanium	Cortical bone	Trabecular bone	Resin
Young's modulus (E) – [MPa]	110000	13700	1370	3520
Poisson ratio (ν) – [-]	0.33	0.3	0.3	0.4

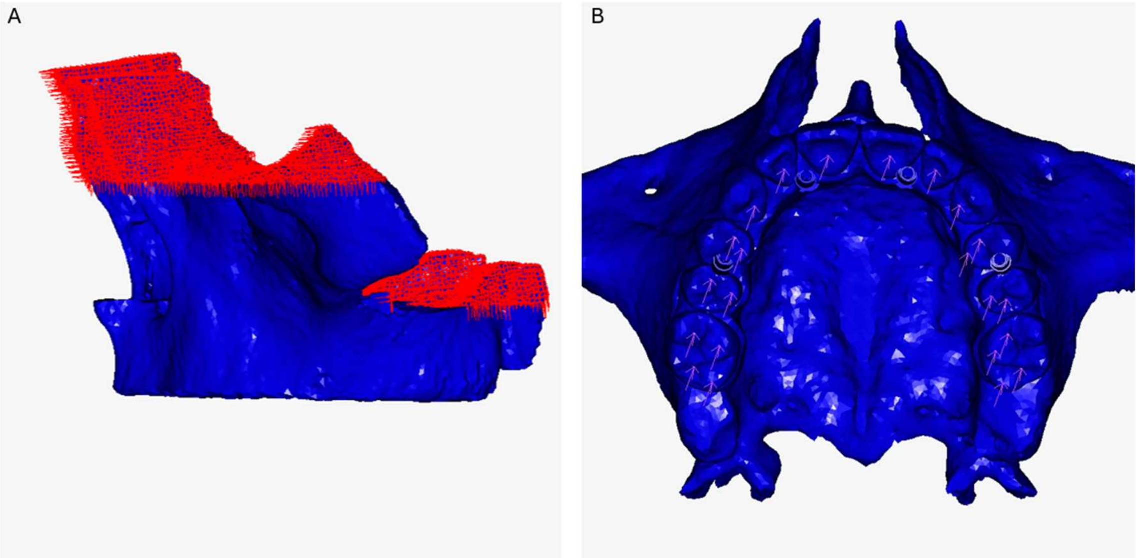


Figure 3. A) Finite element model constrain. B) Load distribution on occlusal surface of prosthetic teeth.

Models were fully constrained in all directions at nodes on the superior border of the maxillary bone (Figure 3A). Two different loading magnitude were simulated. In the first, 20N have been applied in each of the 22 loading points, evenly distributed on the occlusal surface of the prosthetic teeth, reaching a total loading of 440N, evenly distributed on the occlusal surface of the prosthetic teeth. In the second, a total of 550N was applied as the same, 25N each point (Figure 3B). A total of 24 models have been analyzed, varying the distal implant tilting (i.e. 30, 45 and 60 degrees of inclination), length (10 and 13 mm), loading magnitude (440 and 550N) and clinica situation (immediate and delayed loading).

The data for peak equivalent strain (EQV strain) in the bone, bone volume above 4000με and peak equivalent von Mises stress (EQV stress) in the abutment screw were assessed. The finite element analysis and postprocessing were performed for each model by Marc/Mentat (2010 MSC Software). The Jamovi software was used to perform the statistical analysis of this study. The isolated and associated effect of the independent variables (Implant length, implant angulation, and occlusal loading) on the dependent variables (EQV strain, bone volume above 4000με, EQV stress in abutments, abutment screws, bar retaining screws) was evaluated using the ANCOVA. The post test of Tukey considered the implants length and angulation as independent variable, while the occlusal load was considered as a covariate. Significance level set at 5%.

Results

Table 2 presents the values for the peak EQV strain in bone, volume of bone affected by a strain above 4000 μƐ (mm^3), and the peak EQV stress in the abutment screw for immediate and delayed loading situations, with 440 N and 550 N loading magnitudes.

Table 2: Strain values for bone (volume above 4000μƐ and peak EQV strain) and peak

EQV stress in abutment screw for all simulated models. Different letters represent statistically significant differences.

Implant Position	Loading (N)	Implant Length (mm)	Angulation (degrees)	Immediate Loading			Delayed Loading		
				Peak EQV Strain(με)	Bone volume above 4000με (mm^3)	Peak EQV stress abut screw (mpa)	Peak EQV Strain(με)	Bone volume above 4000με (mm^3)	Peak EQV stress abut screw (mpa)
1	440	10	30	6373.18	0.0005	23.87[a]	3616.69[a]	0.00	22.58[a]
	440		45	5613.07	0.08	45.07[b]	5136.46[b]	0.04	43.21[b]
	440		60	5658.00	0.06	34.94[b]	4582.33[b]	0.02	42.55[b]
	440	13	30	4211.02	0.0024	23.48[a]	3527.90[a]	0.00	22.87[a]
	440		45	5777.45	0.08	43.30[b]	5200.01[b]	0.04	43.77[b]
	440		60	5582.06	0.06	40.55[b]	4639.05[b]	0.01	36.01[b]
	550	10	30	8033.36	0.01[a]	28.64[a]	4491.05[a]	0.00[a]	26.88[a]
	550		45	6504.97	0.12[b]	53.70[b]	6504.97[b]	0.12[b]	53.70[b]
	550		60	7193.12	0.18[b]	50.55[b]	5684.75[b]	0.06[b]	41.67[b]
	550	13	30	5850.08	0.01[a]	28.72[a]	4307.04[a]	0.01[a]	26.94[a]
	550		45	7398.54	0.22[b]	56.35[b]	6507.51[b]	0.10[b]	54.25[b]
	550		60	7122.22	0.18[b]	43.07[b]	5742.74[b]	0.07[b]	43.37[b]
4	440	10	30	9346.56[a]	1.51[a]	18.16[a]	9439.45[a]	0.78[a]	17.43[a]
	440		45	14215.80[a,b]	4.89[b]	34.48[b]	10532.60[a,b]	2.70[b]	34.40[b]
	440		60	16947.60[b]	8.78[c]	29.27[b]	11876.10[b]	3.63[b]	28.36[b]

440	13	30	9027.87^{a}	1.12^{a}	17.74^{a}	7854.37^{a}	0.74^{a}	17.00^{a}
440		45	13473.90^{a,b}	5.56^{b}	33.33^{b}	9702.72^{a,b}	2.55^{b}	34.35^{b}
440		60	18591.70^{b}	9.90^{c}	34.91^{b}	13204.90^{b}	3.26^{b}	27.66^{b}
550	10	30	12193.70^{a}	1.89^{a}	21.63^{a}	11860.80^{a}	1.24^{a}	20.06^{a}
550		45	13195.10^{a}	8.70^{b}	50.46^{c}	13195.10^{a,b}	3.86^{b}	50.46^{c}
550		60	21247.70^{b}	12.01^{c}	34.96^{b}	14694.00^{b}	5.28^{c}	33.61^{b}
550	13	30	11343.10^{a}	1.90^{a}	20.68^{a}	9791.69^{a}	1.07^{a}	19.59^{a}
550		45	17289.80^{a}	7.94^{b}	45.18^{c}	12247.80^{a,b}	4.19^{b}	52.06^{c}
550		60	23529.40^{b}	13.16^{c}	34.89^{b}	16467.70^{b}	4.63^{b}	33.80^{b}

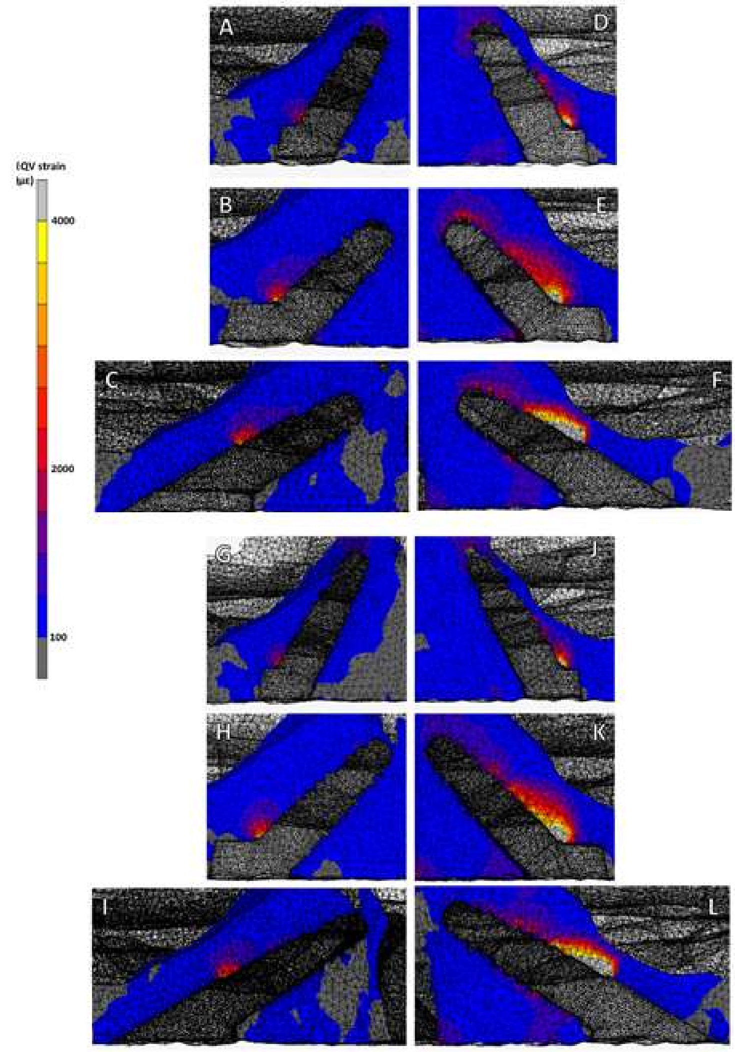
Loading magnitude significantly affected the EQV strain in bone, regardless of distal implant length, inclination degree, and clinical situation. Implant length presented no influence on distal peri-implant bone strain comparing different distal implant inclinations.

For the peak EQV strain in bone in immediate loading simulations, no difference was observed for implant 1 for different loading magnitudes. On the other hand, for implant 4, a 30-degree inclination showed the lowest value of peak EQV strain in bone and bone volume affected by a strain above 4000 με, compared to 45- and 60-degree inclinations, in most of the simulated situations. The same pattern was observed for implant 1 for bone volume affected by a strain above 4000 με for a 550 N loading magnitude. No significant differences in either the peak EQV strain in bone or bone volume affected by a strain above 4000 με were observed for 45 and 60 inclination degrees, independently of loading magnitude.

In delayed loading situations, both the peak EQV strain in bone and bone volume affected by a strain above 4000 με were higher for 45 and 60 inclination degrees compared to 30 inclination degrees. Also, no significant differences were observed for 45 and 60 inclination degrees.

Figure 4 demonstrates the strain distribution in peri-implant bone, comparing different distal implant inclination degrees and lengths for a 550 N loading simulation. It is possible to observe that the peri-implant strain concentration increases from 30 to 60 degrees of distal implant inclinations. The distal implant length does not significantly influence peri-implant strain concentration.

Figure 4. Peri-implant bone strain distribution in distal implants, comparing different inclination degrees and implant length. Note that a higher strain concentration is observed with the increase in the inclination of the distal implant. Implant length do not affect peri-implant strain concentration. 10mm implants with 640N loading (A-F) 13mm implantes with 640N loading (G-L) A-G) 30 degrees implant position 1; B-H) 45 degrees implant position 1; C-I) 60 degrees implant position 1; D-J) 30 degrees implant position 4; E-K) 45 degrees implant position 4; F-L) 60 degrees implant position 4.



The 30-degree distal implant inclination presented a significantly lower peak EQV stress compared with 45 and 60 inclination degrees in most model simulations. No significant differences have been observed comparing 45 and 60 inclination degrees, regardless of loading magnitude and clinical situation.

Discussion

The present finite element analysis (FEA) study evaluated the biomechanical behavior of a maxillary full-arch implant-supported rehabilitation using the all-on-four concept, considering different distal implant angulations (30°, 45°, and 60°), lengths (10 mm and 13 mm), and loading conditions (550 N and 640 N). The central alternative hypothesis—that increasing implant angulation would lead to greater stress and strain—was confirmed by the results. Greater implant angulations were associated with increased strain in the peri-implant bone, particularly under late loading conditions. In most cases, strain values exceeded the physiological overload threshold associated with bone resorption (Duyck et al., 2001), especially at 45° and 60° inclinations. Increased implant angulation also led to higher stress concentrations within the implant components, specifically in the abutment screw. Although these stresses increased with both angulation and load magnitude, they remained below the fracture limit of titanium (Yanagida et al., 2009), indicating a low risk of mechanical failure under the simulated conditions. On the other hand, implant length (10 mm vs. 13 mm) had minimal influence on strain distribution in the peri-implant bone or on stress levels in the implant system, suggesting that length is a less critical factor than angulation in this context. Altogether, the simulations demonstrated that the use of posterior tilted implants in the all-on-four configuration can lead to strain overload in the surrounding bone when high angulations are employed, particularly under elevated occlusal loads. Lower angulations (e.g., 30°) resulted in more favorable biomechanical outcomes, supporting the clinical recommendation to minimize angulation whenever the patient anatomy allows.

Supporting these findings, an increase in the volume of bone exceeding the 4000 $\mu\varepsilon$ threshold was observed at higher implant angulations. Similar outcomes were reported in previous FEA studies with simplified models (Anitua et al., 2022; Mosharraf et al., 2022), mandible all-on-four models (Tribst et al., 2022), and more similar maxillae conditions (Li et al., 2023; Tezerisener et al., 2024). Brum et al. (2020) also observed variations in stress behavior relative to angulation. Under axial loading, lower stress peaks were associated with 30° angulated implants compared to 0° and 17°, while under oblique loading, the 30° implants showed higher stress. This discrepancy is likely due to differences in cortical bone contact area and support, as implants at 0° and 17° had limited cortical engagement compared to those at 30°, altering load distribution. However, contrasting results were found by Gumrukcu and Korkmaz (2018), who observed reduced stress with increased angulation from 30° to 45°. This was attributed to a shortened prosthetic cantilever in the 45° group. In the present study, all models maintained an identical cantilever length, eliminating this variable, which could otherwise influence stress distribution. Future studies are warranted to further explore the interaction between cantilever length and implant angulation under comparable loading conditions.

Considering that higher angulations can lead to increased stress around implants, it is important to states that accurately standardizing implant angulation in clinical settings remains challenging (Cortes-Breton Brinkmann et al., 2021), as only guided surgery ensures the implant's angulation during installation to allow these comparisons more effectively. It is also necessary to understand whether this higher stress can result in bone loss that would be clinically significant, since previous study have been showed that on angled implants demonstrated a high survival rate at the implant level (97.4%) after 17 years of follow-up(Uesugi et al., 2023).

In the current FEA, major of the strain was concentrated in the coronal portion of the tilted distal implants. In the same way, Accordingly, Pessoa et al. (2011), evaluating the influence of different implant body designs on the biomechanical environment of immediately and delayed loaded implants in the superior central incisor region, showed that the strains were mainly concentrated in the coronal region of the implants. The authors argued that, as the applied loading was oblique to the implant body, only moderate amounts of strain were transmitted through the implant body, especially for osseointegrated implants, in which the bone-implant interface was simulated as glued. Hence, the characteristics of the cervical portion of the implants (i.e., diameter, presence of threads, connection type) might exert a greater influence of the stress/strain distribution compared to the implant body design, as length.

Systematic revisions (Büyük et al., 2022; Falcinelli et al., 2023) shows that many studies tend to use oblique static forces to try to simulate a more realistic loading condition, but it is necessary to understand that the force applied for implant simulation should also consider its inclination in these types of analysis. In the present study, although the same nodal points were used for force application, the different angulations resulted in a different angle between the force axis and the implant body, this will result in the pattern of stress/strain distribution around the bone, which may be overlooked by various studies.

One of the main biomechanical complications associated with dental implants is abutment screw loosening, a condition that may result from excessive stresses on the screw due to high occlusal loads or, potentially, implant or prosthetic component angulation (Szajek & Wierszycki, 2023). In a taper connection, the lateral wall of Morse-taper abutments helps to dissipate the oblique forces, protecting the abutment screw from excessive stress (Pessoa et al., 2010; Szajek & Wierszycki, 2023). On the other hand, a higher peak EQV stress in abutment screws have been observed for more angulated abutments in the current FEA, which might consequently lead to screw loosening (Bozini et al., 2011; Noda et al., 2013). In this way, clinical studies should be carried out in order to investigate the possible prosthetic complications related to distal angulated abutments.

The increase in peak EQV stress values with higher occlusal loads and angulations observed here remained well below the failure thresholds reported in the literature (400 to 780mpa) (Wu et al., 2023). Nevertheless, an increase in occlusal load has been identified as a contributing factor for screw loosening (Szajek & Wierszycki, 2023). As discussed in a previously study (Pessoa et al., 2017) the evaluation of maximum von Mises and principal stresses remains a standard method to assess the risk of peri-implant bone failure. Evaluating the bone volume subjected to high stress or strain, along with the stress distribution pattern at the interface, may provide more realistic quantitative and qualitative insights into the risks of bone resorption. This can be observed by comparing the peak EQV strain values of the present study and the values of bone volume above the physiological threshold, were there are great peaks of strain but with little volume of potentially resorbed bone. Notably, a pronounced difference in stress distribution was observed between implants placed at position 1 and position 4, with the latter showing evidence of overload. This discrepancy is likely attributable to the complex, heterogeneous bone structure used in the present study, derived from a patient-specific CT scan. Variations in trabecular and medullary bone density, as well as asymmetric anatomical features, may explain the differences in biomechanical response across the arch.

Implant length showed no significant influence on strain distribution in the bone or components, diverging from previous studies (Baggi et al., 2008; Gumrukcu & Korkmaz, 2018; Petrie & Williams, 2005; Robau-Porrua et al., 2020). This difference can be justified due to the presence of oblique loading used in the study (Petrie & Williams, 2005), or when axial loading was presented, different geometries of implants with different lengths were used in the analysis(Baggi et al., 2008). Nevertheless, Baggi et al. (2008) noted that diameter was more important in peri-implant areas that could be affected by overloading, and that increased length reduced stress gradients at cancellous peri-implant bone, being in accordance with other studies (Anitua et al., 2022; Jafarian et al., 2019). One study showed that the difference may be explained due to the presence of oblique loading, different bone mechanical properties (non-homogeneous, anisotropic and linearly elastic) and simplified geometry of the bone(Robau-Porrua et al., 2020). In the present study the boundary condition of loading was axial on the prosthesis, resulting in a different distribution of forces and stresses affecting the implant and its components, unlike when only point loads are applied, add to that the tilting of implants lead to a different distribution of stress and strain to the bone. The difference in bone mechanical properties could result in other differences and studies simulating a non-simplified mechanical property of the bone should be encouraged.

Loading force was a primary determinant of stress and strain (Pessoa et al., 2010). In the present study, axial forces were used on the prosthesis with the intention of simulating a type of occlusion to assess the distribution of forces through the bone. It was observed that a greater force resulted in greater stress for all groups, which is within expectations. It is understood that dynamic forces would be preferable for simulations, as they present a closer approximation to the reality (Falcinelli et al., 2023).

Given the anatomical and biomechanical differences between the maxilla and mandible, direct FEA comparisons are not appropriate. Nonetheless, improved bone quality has been associated with reduced stress (Anitua et al., 2022; Falcinelli et al., 2023), suggesting superior load distribution in mandibular all-on-four cases. This is corroborated clinically by Uesugi et al. (2023), who reported a higher cumulative survival rate in the mandible (97.4%) compared to the maxilla (94.4%) over long-term follow-up.

The present study constructed a complex patient-specific CT-based 3D FEA model, taking into account the heterogeneous bone geometry and density in the different implant sites. These factors might likely explain the significant difference in strain values observed comparing the distal implants in positions 1 and 4, with the latter presenting the highest levels of peri-implant bone strain. However, generic finite element models, designed to emphasize the relative impact of specific implant parameters in comparative analyses rather than absolute in vivo outcomes, may incorporate simplifications of complex realities (such as the exclusion of implant and retaining screw preload, as well as simplified loading directions, distributions, and boundary/interface conditions), positing that proportions and relative effects would adequately represent the actual clinical scenario. This study focused solely on comparing various situations, with the expectation that the relative results would enhance the qualitative understanding of the biomechanics associated with implants.

It is important to acknowledge the limitations inherent to FEA studies. These include the use of static loading, idealized material properties, absence of preloading (torque), and the inability to simulate biological remodeling. Despite these limitations, the present study remains unique in its bone complexity, featuring a heterogeneity in the distribution of trabecular and cortical bone provided by meticulous segmentation, with a patient-specific geometry model, allowing for the evaluation of more realistic geometries. Additionally, the refined contact used between all components of the prosthetic pieces, with exceptional detail, contact, and friction, is a feat that is far from trivial. The current FEA demonstrated that tilted distal implants in all-on-four protocol with greater angulations exhibits a higher peri-implant strain concentration, which potentially represents a clinically risk for greater marginal bone loss. However, a direct extrapolation of a computational analysis to the clinical context is not possible. In addition, it is necessary to understand whether this possible differences in peri-implant bone for diverse distal implants angulations could influence the long-term outcomes of maxillary all-on-for protocols.

Conclusion

Increased angulation of distal implants (45° and 60) resulted in higher stress and strain in the peri-implant bone and implant components compared to lower angulation (30°). The implant length (10 mm vs. 13 mm) did not significantly affect stress or strain distribution in the peri-implant bone or implant system.

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2. CAPÍTULO 2

ARTIGO 2

Avaliação biomecânica de diferentes comprimentos e macroestrutura de implantes na reabilitação de maxilas pela técnica *all-on-four*. Um estudo de análise de elementos finitos.

Biomechanical evaluation of different implant length and macrostructure in an all-on-four maxillae rehabilitation. A finite element analysis study.

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Original Paper: Biomechanical evaluation of different implant length and macrostructure in an all-on-four maxillae rehabilitation. A finite element analysis study.

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Abstract

Purpose: To evaluate the influence of two implant designs and varying distal implant lengths (at 45º angulation) on the biomechanical behavior in edentulous maxilla rehabilitation using the all-on-four technique. Forty finite element analysis (FEA) models of an edentulous maxilla were generated: twenty for immediate loading and twenty for late loading, using two implant designs—Square and inverted buttress threads models (20 models each). Forces of 550 N and 640 N were distributed across 22 points across the occlusion. Distal implants were angled at 45º with lengths of 10, 13, 15, 18, and 22 mm; anterior implants were placed axially with 10 mm implants. The Peak EQV Strain and Bone volume above 4000 µƐ were recorded. Data were analyzed using ANCOVA with Tukey's post hoc test at a 5% significance level ($p < 0.05$). Results: Increased loading significantly raised bone strain. Implant length presented limited effect in strain distribution under late loading. The inverted buttress threads model showed overall lower strain than the square threads model, with significant differences at 22 mm (immediate loading) and at 13 mm and 22 mm (late loading). Qualitative analysis showed the inverted buttress model had better strain distribution at the implant apex. Conclusion: Implant length had minimal influence on strain distribution. Implant design affected load distribution, especially with longer implants. The overall values of strain observed in this study were minimal, so all the implants showed safety in the conditions tested.

Keywords: Dental implants, Biomechanics, Finite Element Analysis.

Introduction

The All-on-Four technique in the maxilla is well established therapy to support a full-arch prosthesis, offering a viable solution for edentulous patient rehabilitation (Uesugi et al., 2023; Yang et al., 2023). This technique typically involves tilting the distal implants to avoid the need for bone augmentation procedures, such as sinus floor elevation (Maló et al., 2005). Long-term success has been reported, with cumulative survival rates ranging from 94.4% to 99.38% over follow-up periods of 4 to 17 years (Uesugi et al., 2023; Yang et al., 2023).

The use of varying implant lengths in the All-on-Four configuration has been investigated in the literature. Increased implant length has been shown to enhance primary stability by improving engagement with the surrounding bone tissue (Lanza et al., 2023). indicate that longer implants may reduce stress in both cancellous and cortical bone (Falcinelli et al., 2023; Robau-Porrua et al., 2020). In this technique, the angulation of distal implants facilitates the use of longer implants, which can engage the apical cortical bone and potentially increase stability (Maló et al., 2005).

However, evidence remains limited regarding whether greater implant length can offset the stress concentrations typically observed with increased implant angulation. Previous FEA studies have indicated that increasing the angulation beyond 30° in distal implants can lead to elevated stress around the implant in the maxilla (Tezerisener et al., 2024), which may contribute to marginal bone loss (Gumrukcu & Korkmaz, 2018). Therefore, it is important to assess whether the use of longer implants in angulated positions can mitigate such stress and improve biomechanical performance in all-on-four rehabilitations.

In addition to implant length and angulation, macrostructural features of implants have also been shown to influence biomechanical performance, stress distribution, and long-term clinical outcomes (Pala et al., 2024). Specifically, implant neck design and thread geometry significantly affect stress distribution in peri-implant bone (Dávila et al., 2019; Sahai et al., 2024; Sousa et al., 2016), potentially reducing bone loss depending on the implant's cervical design (Dávila et al., 2019). Excessive loading can surpass the physiological tolerance of the bone, leading to bone resorption and implant failure (Duyck et al., 2001). Given that force distribution plays a crucial role in these processes, thread geometry becomes a key factor to consider when evaluating different implant designs in terms of force distribution and strain on bone (Niroomand & Arabbeiki, 2020).

To date, only one FEA study has simultaneously assessed implant angulation, length, and number in the context of the All-on-Four technique (Gumrukcu & Korkmaz, 2018). Longer implants were associated with increased stress in the cortical bone, although this outcome was attributed to greater angulations in the same groups (>13 mm implants). (Gumrukcu & Korkmaz, 2018). Other FEA investigations have suggested that implant length plays a minor role in stress distribution (Falcinelli et al., 2023), and studies that report differences often compare short versus conventional implants (Abdel-Halim et al., 2021; Baggi et al., 2008) or involve multiple variables that confound the effect of implant length (Robau-Porrua et al., 2020). Overall, there is no clear consensus in the literature, and there is a notable lack of studies that evaluate implant length in a controlled model with angulated implants.

Recent review studies have highlighted the scarcity of FEA research based on realistic clinical conditions, particularly those involving complex anatomical models of the maxilla (Falcinelli et al., 2023). To the best of the authors' knowledge, no study has evaluated the influence of implant length and macrostructural design in angled implants using a patient-specific finite element model of the edentulous maxilla, incorporating detailed contact interfaces between all implant components. Therefore, the present study aimed to evaluate the influence of two implant designs with different distal implant lengths, tilted at 45°, on the biomechanical behavior of All-on-Four rehabilitations in the edentulous maxilla, using a complex anatomical model.

Materials and Methods

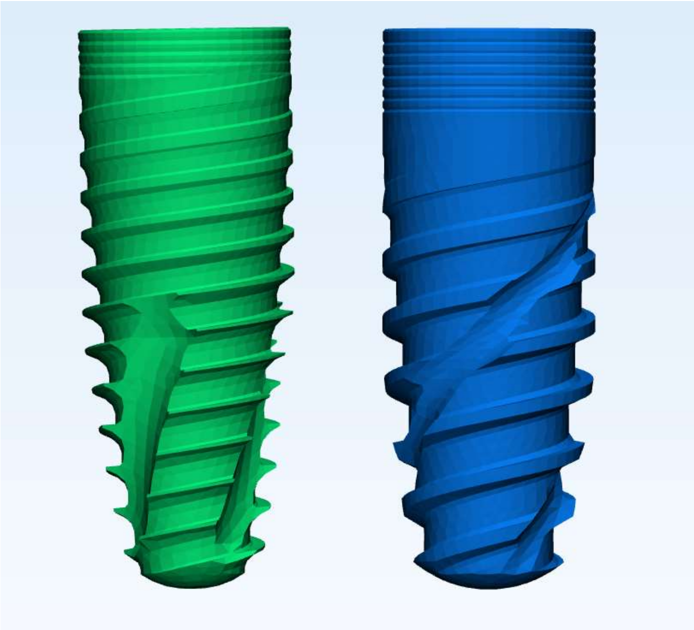
The present study is an in silico finite element analysis of an edentulous maxilla that investigates two types of implant designs (Epikut inverted buttress model and square threads implant model, SIN Implant System, São Paulo, Brazil) and five different implant lengths (10, 13, 15, 18, and 22 mm), all placed at a 45° angulation, under two loading conditions (550 N and 660 N) and in two clinical scenarios of All-on-Four rehabilitation (immediate and delayed loading). The 45° angulation was selected because it allowed the accommodation and evaluation of all implant lengths without anatomical limitations, making it possible to standardize the analysis. Moreover, this setup enabled the assessment of the variables (length and design) performance in an angulated environment, which is characteristic of the all-on-four technique and clinically relevant for posterior implant positioning in the maxilla.

Finite element model

The maxillary geometry was created using a computer tomography (CT) DICOM (Digital Imaging and Communication in Medicine) of a totally edentulous patient, which was segmented and reconstructed using interactive medical imaging software (Mimics 21.0, Materialise, Hassrode, Belgium). The computer-aided design (CAD) of implants and components (abutment, abutment screw, bar retention screw, titanium cylinders) was provided by SIN Implant System and was an exact replica of the commercially available implants with a 3.8 mm diameter SIN Epikut (SIN Implant System, São Paulo, Brazil) and lengths of 10, 13, 15, 18, and 22 mm. The framework beam (i.e., bar) was designed in a computer-aided design program (CAD, Exocad, Align Technology, Germany) as a geometric solid, 3.3 mm high and 1.6 mm thick, in a horseshoe configuration. The prosthesis was also made in CAD and presented cantilevers measuring 7.6 mm from the most distal implant on both sides.

In this study, two different implant macrostructures were analyzed (Fig. 1). Inverted buttress implant features a tapered body design with three concentric rings at the neck region, followed by inverted buttress threads along the implant body. Its antirotational groove extends from the middle third to the apical portion of the implant. Square threads implant also has a tapered body, with seven concentric rings at the neck and square threads along the implant body. In this model, the antirotational groove begins immediately after the concentric rings of the implant neck. According to manufacturer specifications (SIN Implant System, São Paulo, Brazil), the difference in thread geometry between the two models results in approximately 30% greater bone-to-implant contact area for the inverted buttress threads model compared to the square threads model. These distinct design characteristics, particularly in thread shape and distribution, are relevant from a biomechanical perspective and therefore justify the investigation of implant design differences in the present study.

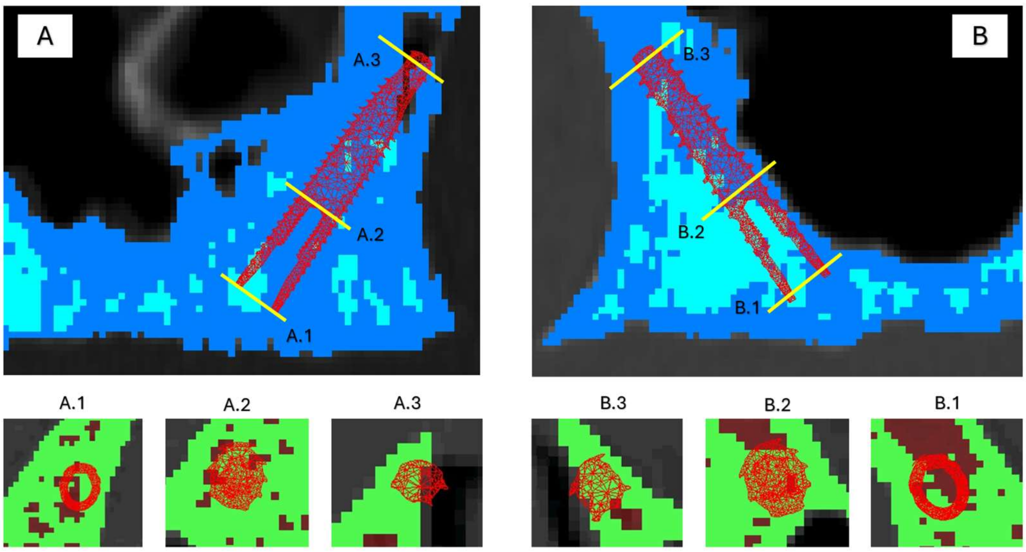
Fig 1. STL models of reverse buttress threads and square threads respectively.



The components were aligned with the implants following the manufacturer's instructions, and the entire set was positioned in an edentulous maxilla in the most ideal locations for implant placement and for testing all distal implant lengths used in the all-on-four technique. Implants 1 to 4 were positioned as follows: implant 1 corresponds to the right distal implant, implant 2 to the right anterior implant, implant 3 to the left anterior implant, and implant 4 to the left distal implant. The prosthesis and bar were aligned with the cylinders; the bar and the cylinders were joined in 3-Matic and subtracted from the prosthesis to ensure a perfect fit. No simplifications were made regarding the implant system's microgeometry.

Considering the bone-implant contact, Figure 2 shows the overall bone distribution for the implants in position 1 (right distal implant) and position 4 (left distal implant) for each implant design. In position 1 (right distal implant), most of the bone in contact is cortical, with some trabecular bone observed at the distal aspect of the implant neck. In position 4 (left distal implant), there is a higher concentration of trabecular bone in contact with the implant body, particularly on the mesial side. Regarding the implant apex, the 18 mm implant in position 1 (right distal implant) shows bone dehiscence at the palatal aspect. The 22 mm implants in both position 1 (right distal implant) and position 4 (left distal implant) present apical bone dehiscence at the palatal bone, with the implant in position 1 (right distal implant) exhibiting a greater extent of implant surface lacking bone contact compared to the implant in position 4 (left distal implant).

Fig 2. Overall bone distribution for the 22mm implant model in sagittal cut. Blue and green represents cortical bone and light blue and red represents trabecular bone. A – implant 1 (distal right), with axial cuts at implant neck (A.1), implant middle point (A.2) and implant apex (A.3). B - implant 4 (distal left), with axial cuts at implant neck (B.1), implant middle point (B.2) and implant apex (B.3).



The model geometry consists of a tetrahedral mesh with 929.423 to 1.047.099 elements and 215.137 to 244.429 nodes, depending on the size of the implant used in the model. Mesh refinement used in the solids varies depending on the details needed. At the bone-implant interface, the bone-mesh was refined to provide a higher degree of detail. The maxilla solid model had the ostectomy and implant placement performed using 3-Matic® software (14.0 Materialise, Hassrode, Belgium). The bone-implant interface had

100% bone-implant contact (BIC), except in areas with bone dehiscence. The abutments were 2 mm in height from the implant shoulder.

The meshing of the model was achieved using Patran® software (2010, MSC Software, Gouda, Netherlands), and any corrections or adjustments necessary in the model were made in 3-Matic® software (14.0 Materialise, Hassrode, Belgium). The bone mesh volume contained tetrahedral elements in either cortical or trabecular bone. The discrimination between both tissues' material properties (i.e., elastic properties) was assigned using density thresholding of gray values from the CT image in Mimics software. Material properties (Young's modulus and Poisson's ratio) used for the materials in the present study were adopted from relevant literature (4, 12) and are described in Table 1. Other aspects, such as the tightening of abutments and the preload in abutment screws and bar retaining screws, were not considered in the present study.

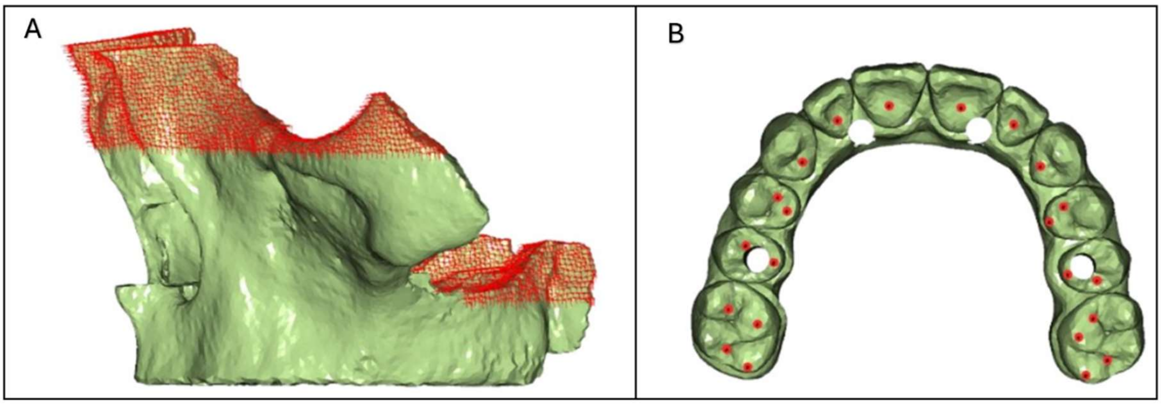
Table 1: Median of the values of the dependent variables analyzed in this study.

Properties	Materials			
	Titanium	Cortical bone	Trabecular bone	Resin
Young's modulus (E) – [MPa]	110000	13700	1370	3520
Poisson ratio (ν) – [-]	0.33	0.3	0.3	0.4

Contact, constraints and loads

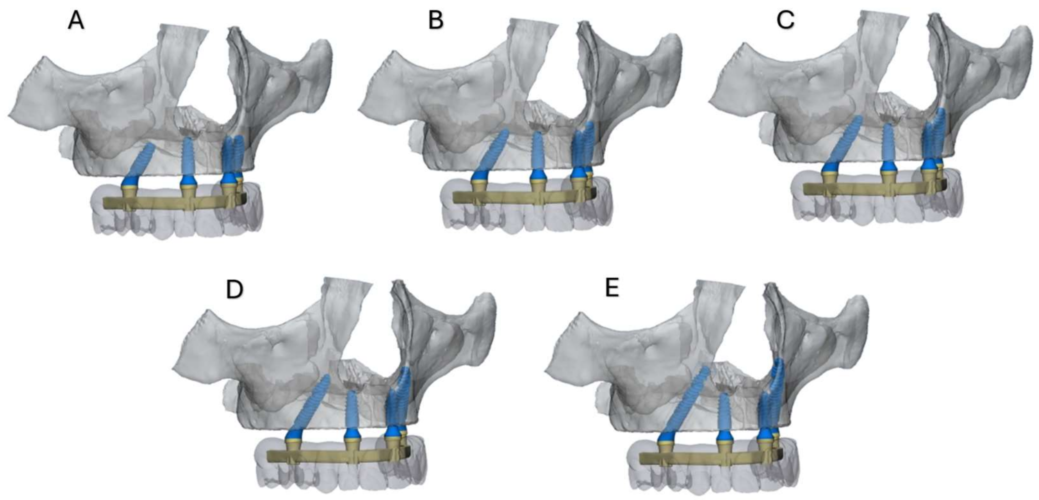
Nonlinear frictional contact elements (Coulomb frictional interface) were used to simulate the contact between the implant-abutment components, adopting a frictional coefficient of 0.5. To simulate the immediately loading condition the bone-implant contact (BIC) adopted a frictional coefficient of 0.3 (Sousa et al., 2016). In the late loaded implants, it was considered that full osseointegration occurred, with contacts considered bonded. This configuration allows minor displacements between components without interpenetration of meshes, resulting in pressure and friction (tangential forces) without tension. The bonded condition does not allow the occurrence of relative motion. This interface condition remained the same regardless of the FEA model.

Fig 3. A) Constraints of the model, in red represents the nodes that have been constrained in all directions. B) Load points distribution with 22 points distributed (16 posterior points and 6 anterior points), in red each dot represents a load point.



Models were fully constrained in all directions at nodes on the superior border of the model (maxilla), specifically on the zygomatic process and the upper maxilla (Fig. 3A). Two loading forces were simulated in the boundary conditions, both applied axially to the prosthesis under a static simulation. The first loading condition consisted of a total load of 550 N and the second of 640 N. The loads were distributed across 22 points: 6 in the anterior region and 16 in the posterior region, corresponding to 22 N per point for the 550 N condition and 29.09 N per point for the 640 N condition (rounded value) (Fig. 3B). Each loading scenario was applied to models with distal implants angled at 45 degrees and in five different lengths (10, 13, 15, 18, and 22 mm) (Fig. 4A–E). All models shared identical configurations regarding cylinder position, cantilever, anterior implant location, and implant diameter (3.8 Ø). This setup generated 10 models under immediate loading and 10 under late loading conditions for each implant design, totaling 40 models. Data collected included peak equivalent strain (EQV strain) in bone and bone volume exceeding 4000 με (in mm^3). All simulations, analyses, and postprocessing were conducted using Marc/Mentat® software (2010, MSC Software).

Fig 4. Model configuration for each distal implant length. A – 10mm implants; B – 13mm implants; C – 15mm implants; D – 18mm implants; E – 22mm implants;



Statistical Analysis

The Jamovi software was used to perform the statistical analysis of this study. The isolated and associated effect of the independent variables (implants length, implant design, and occlusal load) on the dependent variables (EQV strain and bone volume above 4000με) was performed using the ANCOVA test with the post test of Tukey considered the implant length and implant design as an independent variable while the occlusal load was considered as a covariate. All these tests were applied with significance level set at 5%.

Results

In the models simulated in an immediate loading condition considering implant in the position 1 (distal right), the Peak EQV strain was significantly higher for square threads model in the 13 and 18mm lengths. Considering implant in position 4 (distal left), the Peak EQV strain presented differences for implant designs, with the square threads model with the highest values of peak, moreover there were differences for this strain considering the implant length as is shown in table 2. Also, considering bone volume above 4000µƐ (mm³), square threads model presented more bone above this threshold than implant with reverse buttress threads for implants with 22mm length.

Table 2: Effect of implant length on strain of the models in an immediate loading condition.

Implant Position	Implant Design	Loading (N)	Implant Lenght	Peak EQV Strain(µƐ)	Bone volume above 4000µƐ (mm³)
1	Inverted buttress	550	10mm	7089.42	0.41
			13mm	6829.70	0.42
			15mm	7429.31	0.45
			18mm	7434.77	0.40
			22mm	8472.70	0.37
		640	10mm	8406.88	0.63
			13mm	7995.92	0.68
			15mm	10891.90	0.63
			18mm	8563.62	0.63
			22mm	9790.18	0.79
	Square	550	10mm	8507.26	0.40
			13mm	8836.69*	0.34
			15mm	8442.88	0.41
			18mm	9558.73*	0.46
			22mm	9817.49	0.55
		640	10mm	9892.84	0.60
			13mm	10402.22*	0.54
			15mm	9727.53	0.80
			18mm	11159.40*	0.77
			22mm	11295.00	0.80
4	Inverted buttress	550	10mm	4115.83a	0.01
			13mm	6831.06b*	0.03
			15mm	4699.19c	0.06
			18mm	4692.33c	0.04
			22mm	4705.26ac	0.01
		640	10mm	4634.80[a]	0.07

		13mm	7458.63b*	0.07
		15mm	5449.42c	0.08
		18mm	5445.31c	0.08
		22mm	5192.12ac	0.05
Square	550	10mm	4990.95abc*	0.02
		13mm	4759.70b	0.01
		15mm	5332.31c*	0.05
		18mm	5926.56d*	0.07
		22mm	6050.83d*	0.08*
	640	10mm	5783.98abc*	0.05
		13mm	5514.54b	0.06
		15mm	6282.63c*	0.08
		18mm	6935.55d*	0.13
		22mm	7153.19d*	0.15*

* Represent significant difference between the implant design. Lower case letters represent differences between implant length for the variable for each design group.

In the late loading condition, for Implant Position 1 (distal right), the inverted buttress design exhibited an increase in strain with implant length under both 550 N and 640 N loading conditions compared to position 4 (distal left) of the same design. Under 550N and 640N, strain values presented significantly higher strain at 18 and 22 mm compared to shorter lengths of 10 and 13 mm ($p < 0.05$). When comparing implant design the square threads model showed consistently higher strain values than inverted buttress model, in the 10, 13, 18 and 22mm lengths for both loading conditions. Strain values presented significant differences observed at 15 mm with the lower strain value in both loading conditions ($p < 0,05$).

Bone volume above 4000 με showed statistical differences for both implant length and design. For inverted buttress model at 550N and 640N the 15 mm presenting statistical differences from 13 mm. For the square threads model design, bone volume above 4000 με was generally higher than for inverted buttress model, presenting statistical differences for 13 mm and 22 mm implants in relation to implant design. No differences between length in 550N loading condition, while at 640N loading it was observed statistically significant differences between 10 mm and 22 mm implants.

Table 3: Effect of implant length on strain of the models in an osseointegrated condition.

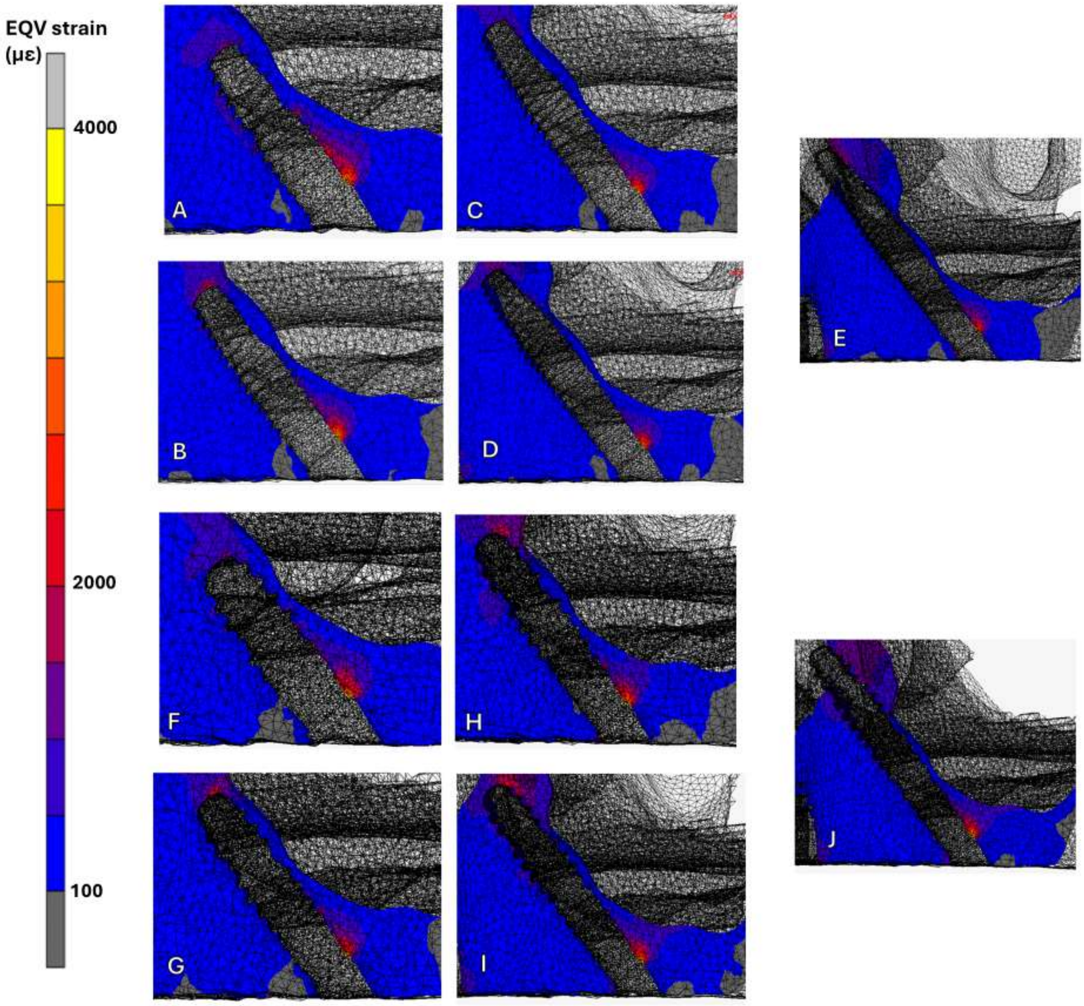
Implant Position	Implant Design	Loading (N)	Implant Lenght	Peak EQV Strain(µƐ)	Bone volume above 4000µƐ (mm³)
1	Inverted buttress	550	10mm	6260.18a	0.14ab
			13mm	6268.73a	0.07a
			15mm	6551.56ab	0.23b
			18mm	6985.07b	0.18ab
			22mm	6923.16b	0.17ab
		640	10mm	7074.12^{a}	0.38ab
			13mm	6904.88^{a}	0.34a
			15mm	7586.22ab	0.45b
			18mm	8148.28b	0.35ab
			22mm	7889.89b	0.37ab
	Square threads	550	10mm	7602.78^{*ab}	0.15a
			13mm	8118.39^{*a}	0.21*ab
			15mm	7038.18b	0.23ab
			18mm	8017.56^{*a}	0.21ab
			22mm	8160.38^{*a}	0.31*b
		640	10mm	8848.66^{*ab}	0.41a
			13mm	9393.02^{*a}	0.43*ab
			15mm	8160.19^{b}	0.46ab
			18mm	9306.84^{*a}	0.47ab
			22mm	9542.56^{*a}	0.50*b
4	Inverted buttress	550	10mm	3053.25^{a}	0.00
			13mm	6181.58*b	0.01
			15mm	4673,9c	0.01
			18mm	4136.16c	0.00
			22mm	3004.19^{a}	0.00
		640	10mm	3542.78^{a}	0.00
			13mm	6690.41*b	0.04
			15mm	5326.47c	0.04
			18mm	4933.90c	0.03
			22mm	3418.15^{a}	0.00
	Square threads	550	10mm	4503.20*a	0.02
			13mm	4093.33a	0.00
			15mm	4494.99^{a}b	0.01
			18mm	4996.70*bc	0.03
			22mm	5295.04*c	0.04
		640	10mm	5179.54*a	0.04
			13mm	4788.54a	0.01
			15mm	5422.83ab	0.05
			18mm	6032.20*bc	0.10

22mm	6085.28*c	0.12

* Represents significant difference between the implant design. Lower case letters represent differences between implant length for the variable for each design group.

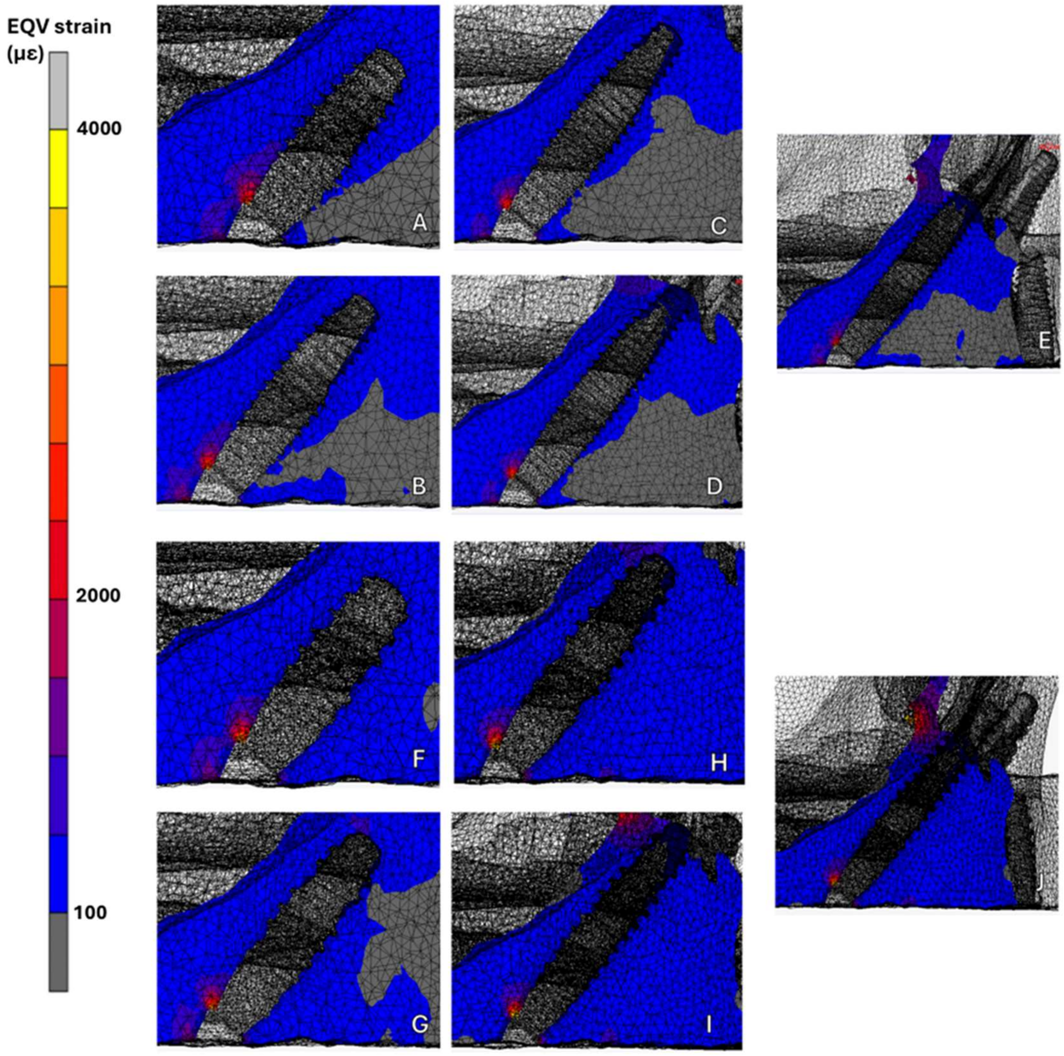
For Implant Position 4 (distal left), the inverted buttress threads model design showed a less pronounced increase in strain with implant length compared to Position 1 (distal right). It was observed no significantly differences between implant design and implant length. Bone volume above 4000 µε also showed no statistical differences for both implant length and design. In figure 5 it is possible to evaluate the overall strain in bone of distal implants at different lengths (10mm – 22mm). In the immediate loading setting, the overall strain pattern is similar between the implant designs, with strain concentrations in the implant neck, at the distal side. Regarding strain distribution in the implant apex, the square threads model presented higher strain concentrations in the canine pillar than the inverted buttress threads model, particularly in the 15 18 and 22mm lengths, although this strain did not surpass the physiological threshold of the bone (4000µƐ). Specifically, at the 22mm implant, the inverted buttress threads model seemed to present higher strain in the implant apex threads, and overall lower strain in the bone compared to the square threads model. This suggests that the inverted buttress threads model leads to a better strain distribution in the bone.

Fig 5. Bone strain distribution in distal posterior implants, in immediate loading condition with 640N loading of implant 4 (distal left), with inverted buttress threads model (A-E) and square threads model (F-J). Square threads model presents greater strain present in implant apex compared to the inverted buttress threads model in qualitative analysis. A and F – 10 mm; B and G – 13 mm; C and H – 15 mm; D and I – 18 mm; E and J – 22 mm.



For the late loading setting (fig. 6) the same pattern is possible to be observed for the implant neck strain distribution in the bone. For the implant apex also the inverted buttress threads model presented lesser strain being distributed in the canine pillar than the square threads model, but that higher strain did not exceed any strain threshold in the bone.

Fig 6. Bone strain distribution in distal posterior implants, in late loading condition with 640N loading of implant 1(distal right), with inverted buttress threads model (A-E) and square threads model (F-J). A and F – 10 mm; B and G – 13 mm; C and H – 15 mm; D and I – 18 mm; E and J – 22 mm.



Discussion

The present FEA study evaluated the effect of different lengths (10, 13, 15, 18 and 22 mm), implant designs (reverse buttress and square threads), and loading conditions (550 N and 640 N) on the biomechanical behavior of distal implants of a maxillae full-arch implant-supported rehabilitation by the all-on-four technique. All prosthetic components, abutments and screws were the same for both types of implants, so those were not analyzed. Under 45 degrees of angulation, increased implant length did not show a substantial influence on strain in peri-implant bone, while reverse buttress threads model consistently exhibited lower strain values compared to square threads model.

The proposed model was developed to simulate implants placed at a 45-degree angulation, aiming to assess the impact of varying implant lengths under this specific configuration. As such, the observed distribution of bone strain appears to be more strongly related to the presence of angulation than to implant length. Supporting this, a study evaluating short implants of 4.5 mm and 5.5 mm versus 10 mm implants found that increased angulation significantly elevated bone strain, regardless of bone type (Type I, II, or III) (Anitua et al., 2022). It was noted that short implants placed without angulation exhibited lower stress than longer angulated implants (Anitua et al., 2022). In a study conducted by Niroomand (2020), various implant parameters were analyzed, including implant length, and it was found that, for straight implants, the length had little influence on the cortical bone. Instead, implant length was more relevant in reducing implant displacement. Other studies also observed that implant length contributed to better stress distribution in trabecular bone (Baggi et al., 2008). Most of the studies described in the literature evaluate implant length in straight configurations. However, when angulation is introduced, as simulated in the present study with implants positioned at 45 degrees, the biomechanical advantage typically associated with increased implant length appears to diminish, a finding that is consistent with previous finite element studies evaluating angled implants (Anitua et al., 2022; Gumrukcu & Korkmaz, 2018). This occurs because the stress tends to concentrate in the crestal module of the implant, particularly in the distal region where the angulated forces are directed. As a result, the distribution of bone strain changes, and the influence of length on the overall biomechanical performance becomes less significant.

The influence of implant geometry was evident in specific conditions: under immediate loading, differences between designs were observed in the 22 mm implant at position 4 (distal left), while under late loading, the 13 mm and 22 mm implants at position 1 (distal right) showed lower stress values for inverted buttress threads model compared to square threads model. One factor that may have contributed to the lower deformations observed for this design is the configuration of its inverted buttress threads, whose thinner profile allows more bone to occupy the space between threads, thereby increasing the bone-to-implant contact area. This reduced thread thickness allows more bone to occupy the space between the threads, as a result, the improved contact likely led to better force distribution and reduced strain in the surrounding bone. Niroomand & Arabbeii (2020) in a sensitivity study, observed that the variation in thread depth may augment the functional contact area between implant and bone, leading to directly reducing strain in the surrounding bone. This better strain distribution may also explain the better strain distribution in implant apex for the inverted buttress threads model in longer lengths (18mm and 22mm).

Distinct strain patterns emerged depending on the clinical loading condition simulated. Under late loading, both implant length and design influenced the peri-implant strain distribution. In contrast, under immediate loading, only the implant design had a noticeable effect. The overall strain was higher in the immediate loading condition, which may have masked the influence of implant length in the model. Additionally, the effects of implant length and design were influenced by local anatomical factors.

Implant position 1 (distal right) presented the highest strain values, which can be explained by the presence of trabecular bone in its distal region, an area subjected to greater mechanical demand. Bone quality plays a crucial role in strain distribution (Anitua et al., 2022; Park et al., 2022), and Park (2022) demonstrated that D4-type bone presents significantly more volume within the range of pathological overload. In contrast, implant position 4 (distal left), although surrounded by a greater amount of trabecular bone, had this bone primarily located in the mesial region. The distal region of this site was composed predominantly of cortical bone, which may have contributed to more favorable strain behavior in this area.

Although trabecular bone is generally associated with increased stress (Liao et al., 2016; Marcián et al., 2014), the presence of higher-quality bone in regions of high mechanical demand such as the distal region of the implant neck appears to enhance strain distribution. This finding highlights the importance of using anatomically specific models, as the arrangement of cortical and trabecular bone is not always as clearly defined as in the simplified models often reported in the literature.

To ensure consistency across groups, implant positioning was standardized to accommodate the various lengths, even though for the 22mm the placement was not ideal due to the presence of bone dehiscence in the apex of the implant. Nonetheless it was possible to represent that longer implant will not necessarily result in implant being placed in the most ideal bone type, and that could lead to greater strains compared to lower lengths, even though it was a small effect.

Overall, an increase in loading conditions was observed to significantly increase the strain encountered in peri-implant bone. Implant 1 (distal right) presented greater overall strain than implant in position 4 (distal left), this is mostly explained due to the overall differences in bone quality and trabecular bone distribution. Specifically, the presence of trabecular bone in the distal portion of the crest module of implant 1 (distal right) resulted in a greater accumulation of deformations, due to this being the region of highest demand and the bone having a lower capacity to distribute these forces. Furthermore, the strain overload in bone was considered any bone element with more than 4000µƐ that would result in a bone resorption, as noted by in vivo study (Duyck et al., 2001).

Nevertheless, the maximum values exceeding the bone strength threshold remained below 1 mm³, which suggests minimal to no clinical impact on the long-term survival of the implants. Therefore, both implant models and all lengths studied may be considered biomechanically viable for clinical use. This can even be supported by long-term retrospective clinical studies with over 4 to 10 years of follow-up, which report survival rates of up to 97% for short implants (<10 mm) and up to 98% for implants up to 18 mm in length (Uesugi et al., 2023; Yang et al., 2023).

It is understood that implant geometry plays an important role in bone stress and deformation (Niroomand & Arabbeiki, 2020; Sousa et al., 2016). Therefore, the results discussed and considered should take this geometry into account and may not be generalized to all implant types. Additionally, the model includes certain simplifications of reality, such as the assumption of static loading forces, simplified material properties for bone, the absence of preload in the model's screws, and the lack of an algorithm for bone remodeling and resorption. Despite these limitations, the present study incorporated cortical and trabecular bone density variations with patient-specific segmentation, resulting in a personalized geometry that better represents a real-world scenario.

Conclusion

In the present finite element analysis, implant length showed limited influence on peri-implant bone strain, particularly under immediate loading conditions. Implant design had a greater impact, wit inverted buttress threads model presenting lower strain values compared to square threads model, especially in the 22 mm configuration. The increased bone-to-implant contact observed in inverted buttress threads model was associated with a more favorable strain distribution and better qualitative strain distribution at implant apex in longer lengths (18mm and 22mm). Across all tested conditions, the volume of bone exceeding the strain threshold remained below 1 mm³. Therefore, none of the evaluated implant lengths or designs resulted in strain values indicative of clinically relevant overload within the parameters of this study.

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CONSIDERAÇÕES FINAIS

O objetivo desta dissertação foi avaliar a influência biomecânica dos implantes distais em reabilitações do tipo All-on-Four, considerando as variações na angulação desses implantes, bem como o impacto do comprimento dos implantes inclinados. Além disso, analisou-se a influência de diferentes macrogeometrias nessas condições.

Inicialmente, no Capítulo 1, foi investigada a influência de diferentes angulações dos implantes (30º, 45º e 60º) e de uma pequena variação no comprimento (10 mm e 13 mm). Observou-se que o aumento da angulação afetou significativamente a deformação no osso peri-implantar. Esse efeito também foi observado nos componentes protéticos, embora os valores encontrados não tenham atingido níveis capazes de causar danos estruturais. A variação no comprimento dos implantes não demonstrou influência significativa nas condições avaliadas, provavelmente devido à interferência do efeito combinado da força oclusal e da angulação. Destaca-se que a concentração das deformações ocorreu principalmente na crista óssea, na região inicial de contato osso-implante.

Com base nesses achados, no segundo estudo, a variável "angulação" foi isolada, mantendo-se o ângulo do implante fixo em 45º. As análises passaram a focar exclusivamente nas variações de comprimento e macrogeometria dos implantes. Novamente, o comprimento dos implantes não apresentou influência relevante. Embora algumas diferenças quantitativas tenham sido observadas, elas foram atribuídas, em grande parte, à geometria do implante e à qualidade óssea local. Foi possível observar, inclusive, que implantes mais longos não eram, necessariamente, instalados em regiões de melhor qualidade óssea. Em alguns casos, isso resultou em exposição (deiscência) do ápice dos implantes mais longos (>18 mm).

Em ambos os estudos, a força oclusal foi a variável de maior influência, conforme esperado. Também se observou uma diferença expressiva entre as deformações nos implantes posicionados nas regiões 1 e 4. No Capítulo 1, essas diferenças foram atribuídas principalmente à geometria e qualidade óssea da região. Já no Capítulo 2, uma análise mais detalhada da qualidade óssea evidenciou que a presença e a localização do osso trabecular são determinantes para a distribuição e concentração das deformações. Esse achado reforça a importância da utilização de modelos de elementos finitos individualizados para avaliar com maior precisão as deformações ósseas. Vale destacar que a estrutura do osso trabecular e cortical não é tão bem delimitada como frequentemente considerado na maioria dos estudos com elementos finitos, especialmente na maxila, que apresenta grande variabilidade na qualidade óssea.

Assim, mesmo com as limitações inerentes à simplificação do modelo biológico e das propriedades mecânicas do osso, a representação mais fidedigna da interação entre osso trabecular e cortical permitiu maior sensibilidade ao modelo de elementos finitos, aproximando os resultados das simulações à realidade clínica.

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ANEXOS

CENTRO UNIVERSITÁRIO DO TRIÂNGULO - UNITRI

PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: Avaliação clínica de diferentes métodos de reabilitação de maxila atróficas por meio de próteses implantossuportadas

Pesquisador: Roberto Sales e Pessoa

Área Temática:

Versão: 1

CAAE: 68368622.0.0000.5565

Instituição Proponente: ASSOCIACAO SALGADO DE OLIVEIRA DE EDUCACAO E CULTURA

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 6.280.416

Apresentação do Projeto:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Objetivo da Pesquisa:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Avaliação dos Riscos e Benefícios:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Comentários e Considerações sobre a Pesquisa:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Considerações sobre os Termos de apresentação obrigatória:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Conclusões ou Pendências e Lista de Inadequações:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Considerações Finais a critério do CEP:

PROJETO APROVADO SEGUINDO TODOS OS PRECEITOS ÉTICOS

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
Informações Básicas do Projeto	PB_INFORMAÇÕES_BÁSICAS_DO_PROJETO_2041991.pdf	16/11/2022 22:31:48		Aceito
TCLE / Termos de Assentimento / Justificativa de Ausência	TCLE.docx	16/11/2022 22:31:33	Roberto Sales e Pessoa	Aceito
Outros	Curriculo_Roberto.pdf	16/11/2022 22:27:40	Roberto Sales e Pessoa	Aceito
Outros	Curriculo_Guilherme.pdf	16/11/2022 22:27:16	Roberto Sales e Pessoa	Aceito
Outros	Carta_encaminhamento.pdf	16/11/2022 22:27:02	Roberto Sales e Pessoa	Aceito
Declaração de Instituição e Infraestrutura	Declaracao_Inpes.pdf	16/11/2022 22:26:21	Roberto Sales e Pessoa	Aceito
Declaração de Pesquisadores	Termo_equipe.pdf	16/11/2022 22:26:09	Roberto Sales e Pessoa	Aceito
Projeto Detalhado / Brochura Investigador	Projeto_all_on_four.docx	16/11/2022 22:25:49	Roberto Sales e Pessoa	Aceito
Folha de Rosto	Folhaderostoassinada.pdf	16/11/2022 22:25:35	Roberto Sales e Pessoa	Aceito

Situação do Parecer:
Aprovado

Necessita Apreciação da CONEP:
Não

UBERLANDIA, 04 de Setembro de 2023

Assinado por:
Claudiney do Nascimento
(Coordenador(a))