UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
Campus de São José dos Campos
Instituto de Ciência e Tecnologia

JOÃO PAULO MENDES TRIBST

COMPORTAMENTO BIOMECÂNICO DE IMPLANTES RETOS E ANGULADOS SOBRE CARGAS AXIAIS E NÃO AXIAIS POR ANÁLISE DE ELEMENTOS FINITOS E EXTENSOMETRIA LINEAR

2017

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Dissertação apresentada ao Instituto de Ciência e Tecnologia, Universidade Estadual Paulista (Unesp), Campus de São José dos Campos, como parte dos requisitos para obtenção do título de MESTRE, pelo Programa de Pós-Graduação em ODONTOLOGIA RESTAURADORA, Área de Prótese Dentária.

Orientador: Prof. Tit. Renato Sussumu Nishioka

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BANCA EXAMINADORA

Prof. Tit. Renato Sussumu Nishioka
Universidade Estadual Paulista "Júlio de Mesquita Filho" - Unesp
Instituto de Ciência e Tecnologia
Campus de São José dos Campos

Prof. Adj. Alexandre Luiz Souto Borges
Universidade Estadual Paulista "Júlio de Mesquita Filho" - Unesp
Instituto de Ciência e Tecnologia
Campus de São José dos Campos

Prof. Dr. Francisley Ávila Souza
Universidade Estadual Paulista "Júlio de Mesquita Filho" - Unesp
Faculdade de Odontologia
Campus de Araçatuba

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"Uma pessoa inteligente resolve um problema, um sábio o previne."

Albert Einstein

SUMÁRIO

Tribst JPM. Comportamento biomecânico de implantes retos e angulados sobre cargas axiais e não axiais por análise de elementos finitos e extensometria linear [dissertação]. São José dos Campos (SP): Universidade Estadual Paulista (Unesp), Instituto de Ciência e Tecnologia, 2017.

RESUMO

Este trabalho buscou estudar as microdeformações geradas ao redor de implantes de hexágono externo durante carregamentos axiais e não axiais, variando-se a angulação dos implantes, utilizando a análise por elementos finitos e a extensometria linear como ferramentas. Inicialmente modelos 3D de diferentes próteses fixas foram construídos a fim de se permitir uma correlação dos resultados encontrados no modelo simplificado com o modelo anatômico e assim validar a geometria da prótese utilizada no estudo. Após a confirmação dos resultados de tensão similar entre as próteses na região dos implantes e do bloco, o modelo da prótese simplificada foi definida como válida. Em seguida, um modelo de bloco de poliuretano foi criado e duplicado. Implantes com conexão de hexágono externo (HE) foram modelados e em um bloco representados perpendiculares à superfície enquanto que em outro bloco foram colocados com inclinação de 17°. Foram modelados também intermediários do tipo mini pilar cônico retos e angulados conforme a inclinação dos implantes. Por último, foi utilizado o modelo de supraestrutura previamente validada para ambos os grupos, na qual a carga foi incidida. Todos os constituintes foram considerados perfeitamente simétricos, sólidos, isotrópicos. Os modelos receberam cargas de 300 N/cm em pontos axiais e não axiais através do software de análise por elementos finitos para se verificar a tensão máxima principal e as microdeformações. Em seguida, através da análise experimental de extensometria, dois blocos de poliuretano foram confeccionados e receberam três HE cada, bem como, respectivos mini pilares cônicos de acordo com a inclinação dos implantes instalados. Então, uma supraestrutura metálica, idêntica ao modelo computacional foi fundida em NiCr e parafusada sobre os implantes com torque de 10 N/cm. Foram aplicadas cargas de 300 N/cm durante 10 segundos em pontos axiais e não axiais. Para mensurar as microdeformações, foram colados quatro extensômetros na superfície de cada bloco tangenciando os implantes. Os dados obtidos foram analisados estatisticamente através dos testes ANOVA e Tukey (α=5%). Os resultados encontrados pela extensometria mostram que existe diferença significante entre o uso de implantes retos ou inclinados ($p<0,005$) em uma prótese fixa. Através da correlação das metodologias, pode-se observar que o grupo com implantes inclinados atinge picos de tensão acima do limite fisiológico.

Palavras-chave: Análise por elementos finitos. Implantes dentários. Prótese fixa sobre implante.

Tribst JPM. Behavior of implants straight and angled with axial load and non-axial, on finite elements and linear strain gauge analysis [dissertation]. São José dos Campos (SP): São Paulo State University (Unesp), Institute of Science and Technology, 2017.

ABSTRACT

This work aimed to study the microstrains generated around external hexagon implants during axial and non-axial loads, varying the angulation of the implants, using finite element analysis and linear strain gauge as tools. Initially 3D models of different fixed prostheses were constructed in order to allow a correlation of the results found in the simplified model with the anatomical model and thus validate the geometry of the prosthesis used in the study. After confirming the results of similar stress between the prostheses in the implants and the block region, the simplified prosthesis was defined as valid. After, a polyurethane block model was created and duplicated. Implants with external hexagon connection (HE) were modeled and inserted perpendiculary into one block while in another block, were placed with the inclination of 17 °. Straight and angled mini conical abutments were also modeled according to the inclination of the implants. Finally, the supra-structure previously validated for both groups was used, through which the load was affected. All constituents were considered perfectly symmetrical, solid, and isotropic. The models received a load of 300 N / cm in axial and non-axial points through the finite element analysis software, to verify the maximum principal stress and microstrains. Then, through the experimental analysis of strain-gauge, two polyurethane blocks were prepared and received three HE implants each, as well as respective mini tapered pillars according to the inclination of the installed implants. Then, a metallic superstructure, identical to the computational model, was cast in Ni-Cr and screwed onto the implants with torque of 10 N / cm. The load of 300 N / cm was applied for 10 seconds at axial and non-axial points. To measure the microstrains, four extensometers were glued on the surface of each block by tangential implants. The data obtained were statistically analyzed using ANOVA and Tukey tests (α = 5%). S strain-gauge data showed that there is a significant difference between using straight or angled implants (p <0.005) in a fixed prosthesis. And, through the correlation of methodologies it can be observed that the group with angled implants reaches peaks of tension above the physiological limit.

Keywords: Finite element analys. Dental implants. Fixed prosthesis on Implants.

1 INTRODUÇÃO

A reabilitação protética de pessoas desdentadas sempre foi um dos temas mais complexos na odontologia, pois, envolve tanto os fatores psicossociais como também a função oclusiva adequada. De tal modo, a precoce perda de dentes pode representar impactos sobre a qualidade de vida e modificar o correto funcionamento do sistema mastigatório (Annibali et al., 2010), influenciando a harmonia e manutenção da saúde de cada indivíduo.

Com a possibilidade da reabilitação oral com implantes, de modo que o titânio pode se tornar permanentemente osseointegrado, ou seja, inseparável ao osso (Mavrogenis et al., 2009) e, embora a microarquitetura óssea seja altamente diversificada, mesmo dentro de uma mesma região anatômica, torna-se possível à execução de técnicas cada vez mais complexas de reabilitação oral (Steiner et al., 2014).

Diversos estudos confirmam a confiabilidade e satisfação do tratamento em questão (Adell et al., 1990; Lekholm et al., 2006; Annibali et al., 2010). Porém, alguns fatores podem influenciar positivamente o sucesso da reabilitação, como a colaboração do paciente (Jemt et al., 1991; Smedberg et al.,1996; Sethi, Kaus, 2000; Kim et al., 2005) e até mesmo, a escolha de implantes (Buser et al.,1991).

Existem também fatores capazes de induzir falhas nesse sistema de reabilitação protética, pois, os implantes dentários podem ser submetidos às complicações biomecânicas que prejudiquem a sua função (Gealh et al., 2011; Jemt et al., 2014,); uma vez que, estudos *in vitro* evidenciam que a localização das forças aplicadas sobre a estrutura do implante também afeta a magnitude da microdeformação observada (Wiskott, Belser, 1999; Vasconcellos et al., 2011;

Nishioka et al., 2009, 2010, 2015, 2016) e podem ser mais nocivas do que o acúmulo de biofilme (Isidor, 2006).

Observa-se ainda que a tensão em torno do implante aumenta significativamente se a qualidade óssea for pobre ou se força excessiva for aplicada (Gonda et al., 2014). Pois, todas as forças mastigatórias são diretamente transmitidas ao tecido ósseo e podem induzir remodelações inadequadas tais como perdas ósseas marginais (Sahin et al., 2002; Hekimoglu et al., 2004; Isidor, 2006). Do mesmo modo que, a propagação da carga transmitida ao osso suporte pode ser influenciada negativamente se os implantes estiverem em posições inadequadas (Cehreli, Iplikcioglu, 2002). De tal modo, a incidência da força mastigatória através de uma carga axial é mais favorável, distribuindo as tensões no longo eixo do implante evitando concentrações elevadas de tensões em uma única região (Rangert et al.,1989; Sahin et al., 2002; Isidor, 2006; Campos et al., 2014).

Para correção do posicionamento inadequado dos implantes, o uso de pilares protéticos está descrito como principal opção e deve ser realizado de maneira adequada (Stephens et al., 2014). A escolha de componentes protéticos inadequados influencia na presença de deformações indesejadas ou tensão na estrutura (Brosh et al., 1998; Dubois et al., 2007; Hyo-Sook et al., 2014.).

Para melhor entendimento das cargas distribuídas sobre a estrutura do implante, e deste modo, melhorar o controle sobre as possíveis microdeformações, algumas técnicas vêm sendo empregadas, como: a análise por elementos finitos (FEA) avaliando as distribuições de cargas e tensões (Barbier et al., 1998; Abu-Hammad et al., 2007; Segundo et al., 2009; Lanza et al., 2011; Tang et al., 2012; Matsunaga et al., 2013; Sotto-Maior et al., 2014;) e a extensometria linear (SGA) que mensura a mudança dimensional (Glantz et al., 1993; Cehreli, Iplikçioglu 2002) através de circuitos elétricos empregados para a medição das microdeformações, possibilitando o registro e a interpretação do comportamento mecânico (Vasconcellos et al., 2011; Abreu et al., 2012; Nishioka et al., 2009, 2011, 2015, 2016; Campos et al., 2014).

Nos trabalhos de avaliação de tensões, a utilização de um material simulador de tecido ósseo com mesmo comportamento mecânico e que seja capaz de garantir ao sistema um padrão reprodutível em todos os corpos de prova, torna os resultados mais concretos para inferências sobre a influência das variáveis estudadas. Dentro deste quesito, o poliuretano (Wiskott, Belser, 1999; Myashiro et al., 2011) enquadra-se como material de eleição devido seu módulo de elasticidade e validação científica.

Assim sendo, a correlação de duas metodologias (FEA e SGA) com métodos numéricos de estudo da tensão gerada, permite o direcionamento conciso da interpretação dos resultados para possível elucidação do ocorrido clinicamente (Pesqueira et al., 2014).

Uma vez que é dever do profissional durante a escolha do tratamento estar atento aos fatores prejudiciais, as incidências de cargas pelas quais o implante será submetido, bem como, o entendimento da atuação das mesmas no tecido adjacente.

2 ARTIGOS

2.1 Artigo – Tribst JPM, Rodrigues VA, Borges ALS, Nishioka RS. Validação de uma prótese fixa cantilever simplificada implanto-suportada / *Validation of a simplified implant-retained cantilever fixed prosthesis**

RESUMO

Introdução: Diversos modelos de prótese fixa sobre implantes são utilizados em estudos laboratoriais, porém, um modelo válido pode exibir resultados mais confiáveis. Objetivo: avaliar as tensões e microdeformações geradas em uma prótese fixa de quatro elementos, sob a aplicação de cargas axiais e não axiais utilizando um modelo de prótese fixa implanto-suportada simplificada. Materiais e Métodos: Um modelo tridimensional foi construído contendo três implantes e uma prótese anatômica convencional (G1). O segundo modelo contém o mesmo sistema de implantes, porém, uma prótese simplificada (G2). Uma carga de 300 N foi aplicada em um ponto axial e em um ponto não axial através de um software de análise por elementos finitos (FEA). Resultados: O grupo G2 apresentou diferentes valores de concentração de tensão no corpo da prótese, parafuso de fixação, parafuso de retenção e pilares quando comparado com G1. Dentro de um limite de 10% de aceitabilidade se enquadraram as tensões nos implantes e as deformações ósseas para ambos os modelos de prótese. Conclusão: A prótese fixa simplificada avaliada neste estudo apresenta comportamento biomecânico semelhante a uma prótese anatômica nos implantes e na estrutura óssea ao redor.

Palavras-chave: Análise por elementos finitos. Implantes dentários. Prótese fixa.

ABSTRACT

Introduction: *Several models of fixed prostheses on implants are used in laboratory studies, but a valid model can show more reliable results.* ***Purpose:*** *To evaluate the stress and strain generated in a fixed four-element prosthesis under application of axial and non-axial loads using a simplified implant-supported fixed prosthesis model.* ***Material and Methods:*** *A three-dimensional model was constructed containing three implants with a conventional anatomical prosthesis (G1). The second model with the same implant system received the simplified prosthesis (G2). A load of 300 N was applied at an axial point and a non-axial point through finite element analysis software (FEA).*

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Results: *The G2 group showed different values of stress concentration in the prosthesis, fixation screw, retention screw and abutments when compared to G1. Within a limit of 10% degrees of acceptability, the stress on the implants and the bone strain were enclosed for both models of prostheses.* ***Conclusion:*** *The simplified fixed prosthesis evaluated presents biomechanical behavior similar to an anatomical prosthesis in the implants and in the surrounding bone structure.*

Keywords: Finite element analysis. Dental implant. Fixed Prosthodontics.

1.Introduction

Stress generated around the implant is interesting to the dentist, because in addition to microorganisms capable of generating pathologies, occlusal overload is one of the main causes in osseointegrated implant loss [1].

Finite Elements Analysis (FEA) is the most widely used tool to study stress. This tool is able to elucidate the results in a more secure way and allows [2].

Several authors using FEA used individualized anatomical structures [3,4,5] which make it impossible to replicate the methodology by another researcher who has been interested in the results.

A valid fixed prosthesis model free of anatomic variables can make it possible to simplify laboratory studies, isolate variables of interest, and in particular, allow reproducibility of the structure for *in silico* and *in vitro* studies by other researchers.

There are different ways of performing a mathematical model validation. Direct validation requires comparing the computational simulation with other test results that corroborate the results found. In indirect validation, the comparison is performed with laboratory tests or clinical studies published in the literature [3]. Validation of the model can be confirmed when the results found are similar to the results of the new model tested. [6,7].

Therefore, the objective of this study was to compare the stress generated in a simplified implant-supported fixed prosthesis with an anatomical prosthesis. The hypothesis of the study was that the use of a simplified fixed prosthesis does not present similar biomechanical behavior to a fixed anatomical prosthesis.

2. Materials and methods

2.1 Tridimensional Model

A standard external hexagon implant - HE model (AS TECHNOLOGY TITANIUM FIX - São José dos Campos, Brazil) was created according to the manufacturer's dimensions (3.75x13 mm), using CAD software (Rhinoceros 6.0, SR8, McNeel North America, Seattle, WA, USA). Next, the model was replicated in order to obtain three identical implants with 3 mm distance between them. Each implant received a mini prosthetic abutment with its respective screws.

2.2 Prosthesis Simplification

A simplified prosthesis (3 x 35 x 15mm) used in previous studies [8,9] was placed on the abutments. Openings for the retaining screws of the prosthesis were created on its upper external surface containing 2 mm diameter.

A three-dimensional (3D) model of an anatomical prosthesis was created (Fig 1) for validating the simplified prosthesis, containing the same location of the load application points located on the bar surface.

A three-dimensional block model *(95 x 45 x 20 mm) (Fig 2)* was constructed containing three implants with a conventional anatomical prosthesis (G1). The second model with the same implant system received the simplified prosthesis (G2).

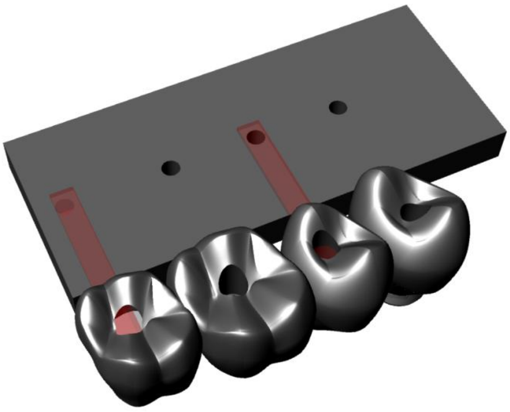

Figure 1: Model of anatomical prosthesis (G1) and simplified prosthesis (G2) showing the same access position to the fixation screw.

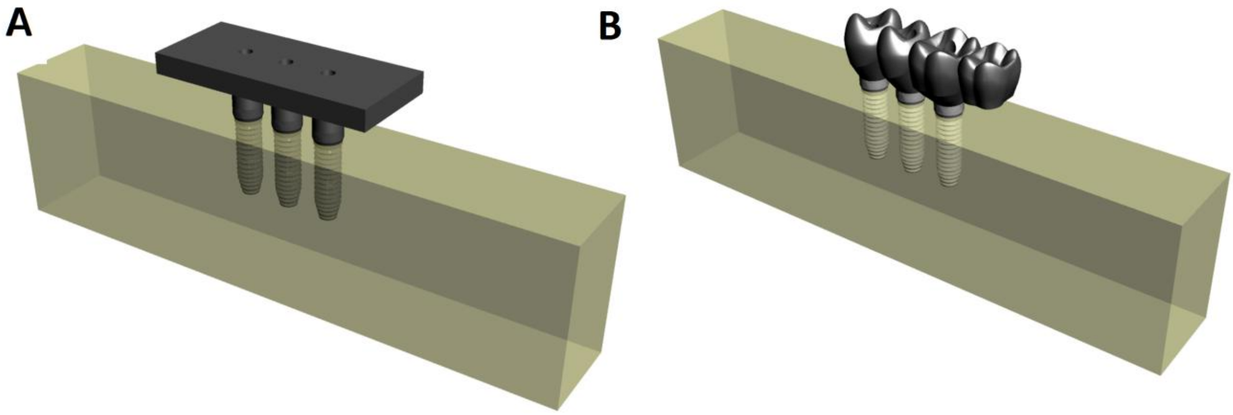

Figure 2: Implants with the A) simplified prosthesis and B) anatomical prosthesis.

2.3 Pre-processing

The material properties were assigned to each solid component as isotropic, homogeneous and linearly elastic. Young's modulus and Poisson's ratio of the materials were reported (Table 1), and all contacts were considered bonded.

Table 1. Materials properties used in the study

	Young Modulus	**Poisson'sratio**	**Reference**
Titanium	110 GPa	0.33	[9]
Nickel Chromium	206 GPa	0.31	[10]
Polyurethane	3.6 GPa	0.3	[11]

2.4 Mesh Generation

Solid geometries were exported to ANSYS software (ANSYS 17.0, ANSYS Inc., Houston, TX, USA) in STEP format and tetrahedral elements formed the mesh. A convergence test of 10% determined 754,936 nodes with 440,893 elements for G1 and 719,255 nodes with 411,921 elements for G2.

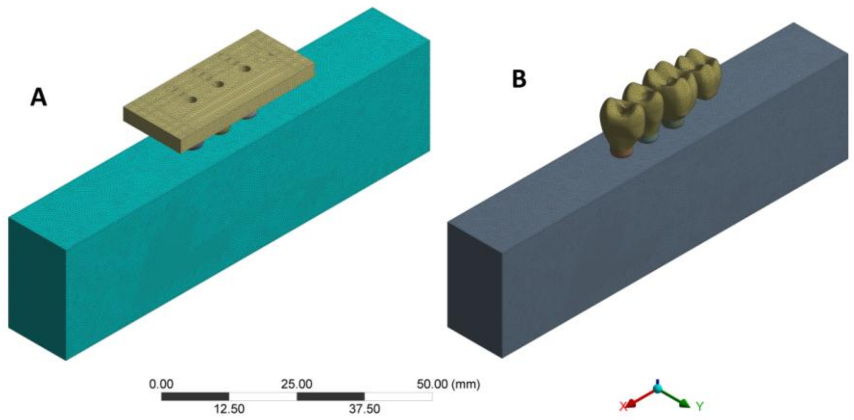

Figure 3: Mesh generated for A) simplified prosthesis, B) Anatomical prosthesis.

2.5 Loading

The load definition followed the defined area in CAD software, with the central screw defined for the axial load application. The central fossa of second molar (cantilever arm) was defined as the non-axial loading application area (Fig 4).

The load (300N) was applied in block Z’s axis direction. The base of the polyurethane block was selected for system fixation, ensuring only movement restriction in Z axis.

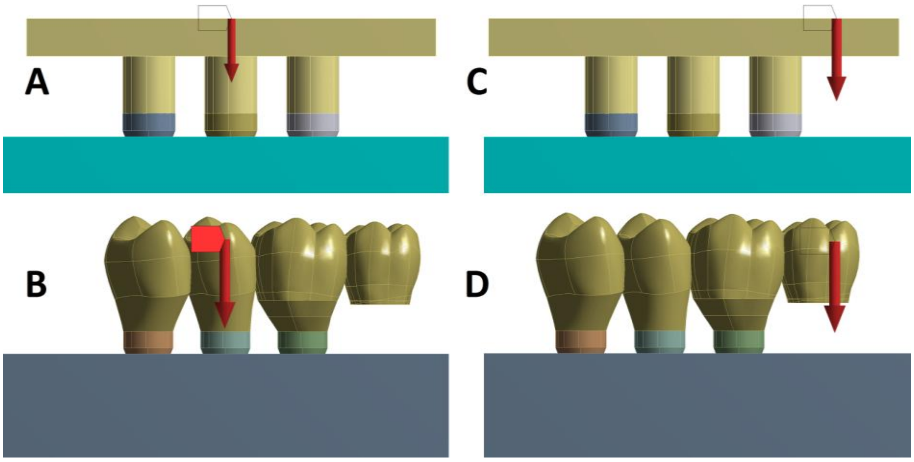

Figure 4: Axial force applied on A) Simplified prosthesis, B) Anatomical prosthesis. Non-axial force applied on C) Simplified prosthesis and D) Anatomical prosthesis.

3.Results

In a general qualitative analysis, system deformation can be verified by the total deformation displacement trend patterns being compared (Fig 5).

For a quantitative and deep analysis, the generated results were obtained by Von Misses stress for ductile solids. For the model simulating human bone tissue, generated microstrains were evaluated.

In comparing the prosthesis models used (Fig. 1), it was observed that stress values were found on the structures expressed in Figures 6 and 7 during axial and non-axial loading, respectively.

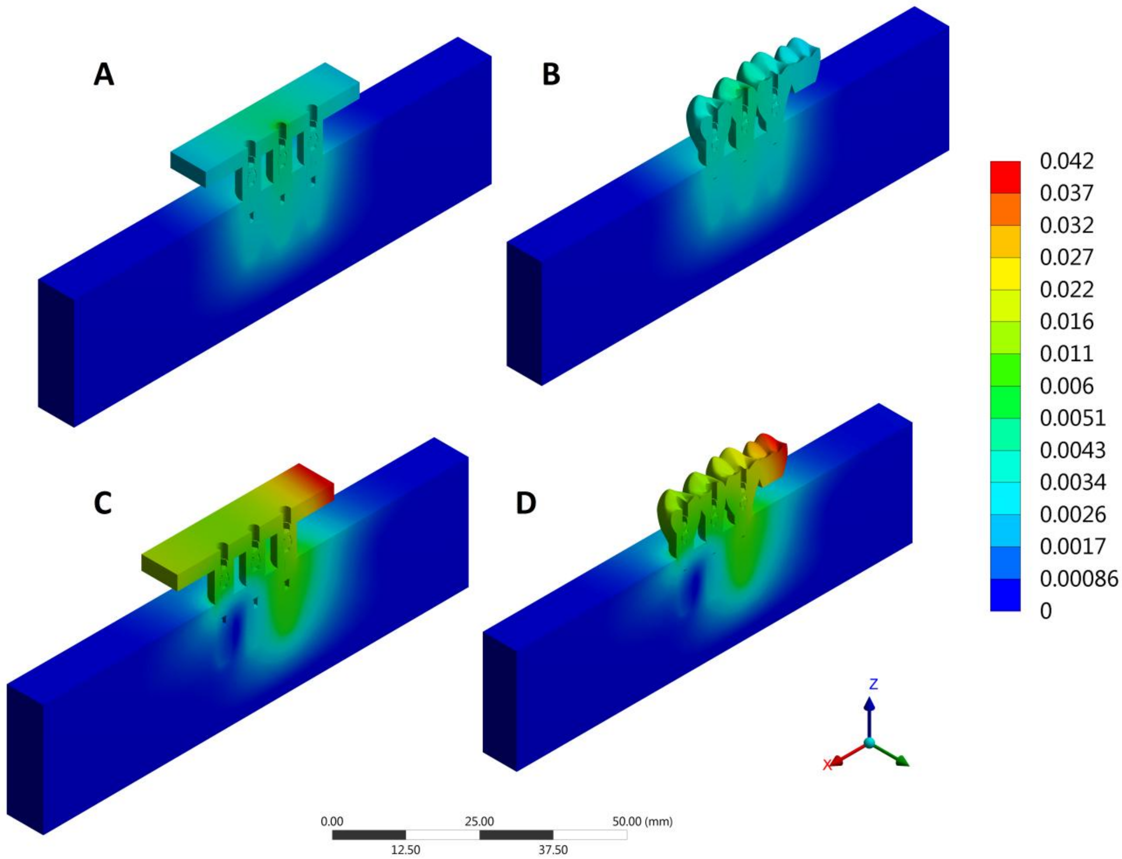

Figure 5: Total deformation on axial loading for A) simplified prosthesis system and B) anatomical prosthesis system. Total deformation on non-axial loading for C) simplified prosthesis system and D) anatomical prosthesis system.

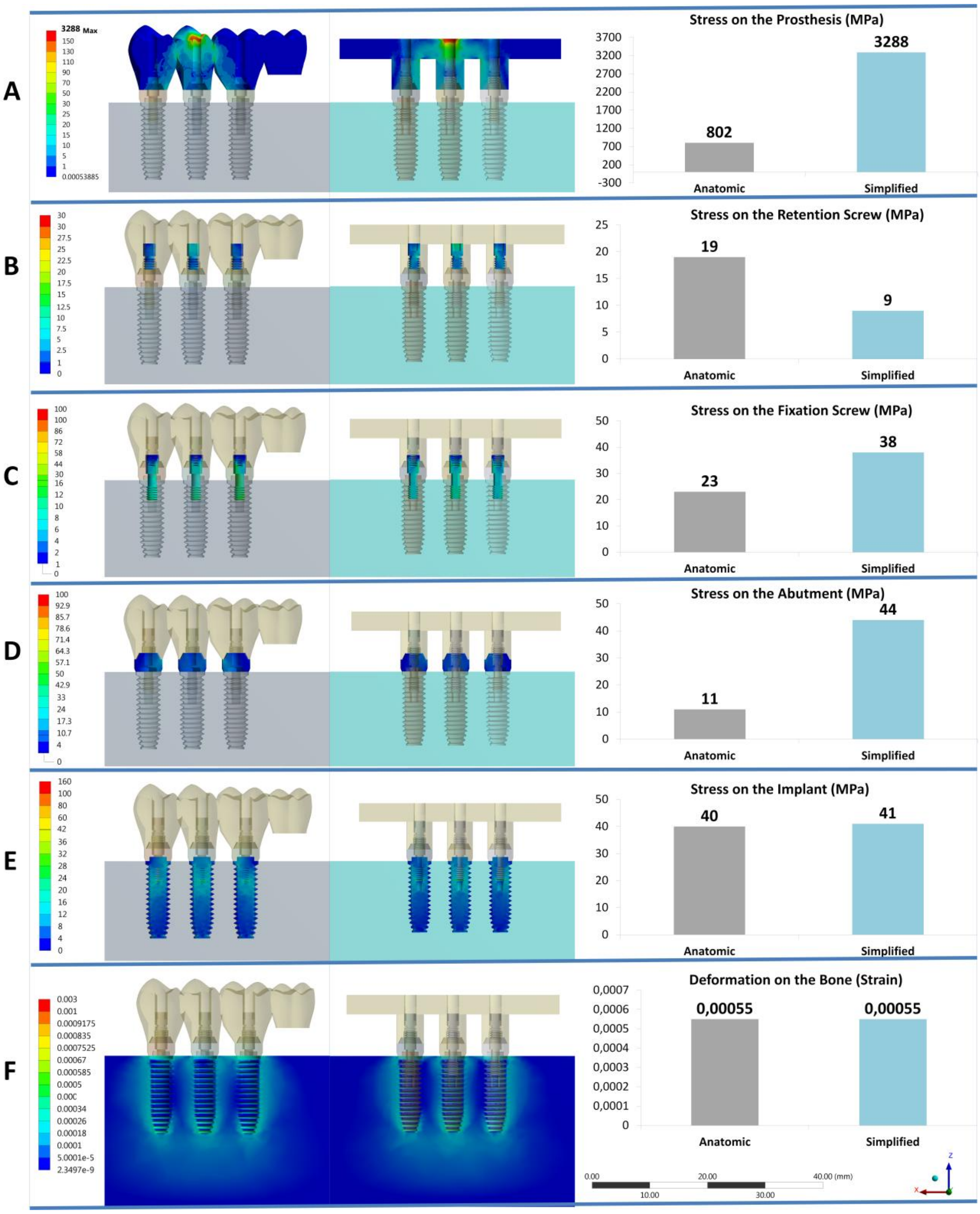

Figure 6: Results obtained during axial loading for the Von-Misses stress comparing both models (anatomical and simplified prosthesis): A) in the prosthesis B) in the retaining screw C) in the fixing screw D) in the abutment E) in the implant and F) the microstrain around the implants in both prostheses.

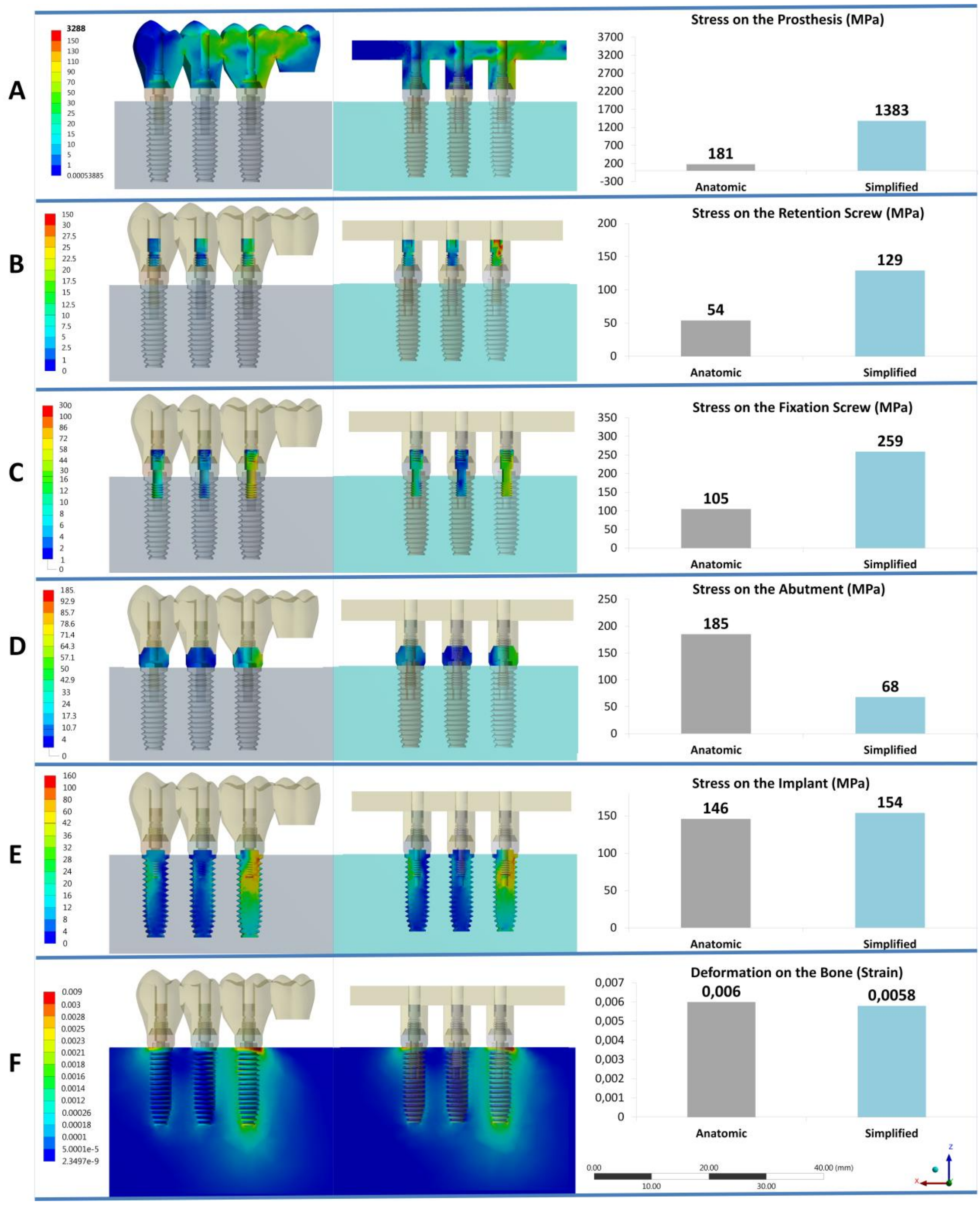

Figure 7: Results obtained during non-axial loading for the Von-Misses stress comparing both models (anatomical and simplified prosthesis): A) in the prosthesis B) in the retaining screw C) in the fixing screw D) in the abutment E) in the implant F) the microstrain around the implants in both prostheses.

4.Discussion

This study aimed to compare the mechanical behavior of a simplified fixed prosthesis with the behavior of a conventional anatomical fixed prosthesis model through a bioengineering tool. Thus, Finite Element Analysis (FEA) was applied as a methodology as it is valid and widely used in studies with dental implants [12-16]. The results confirm that the hypothesis was rejected and suggest that the use of a simplified prosthesis makes it possible to study the stress concentration in implants and adjacent bone tissue. The use of a simplified superstructure that simulates a fixed prosthesis under loads has already been observed in other dental implants [7,8,17,18].

In this study, polyurethane was used as an implant fixation substrate because it is widely used as a bone tissue simulator material in laboratory studies [19-22]. Initially, the coherence of the simplified prosthesis model is verified by comparing the results obtained for the conventional anatomical prosthesis results (Fig 5). It is noted that application of a non-axial load adds a greater amount of displacement energy in both systems, representing a much more detrimental situation for rehabilitation than a purely axial load. When a simplified prosthesis was used on the implants, the total deformation results were very close to those of the anatomical prosthesis, and suggest coherence between the models (Fig. 5). In a more precise analysis, the structures can be analyzed separately to find out which solids in fact exhibited a similar behavior for both prostheses.

Within a maximum 10% difference between the results, it is possible to observe that there is no significant difference in the use of an anatomical or simplified prosthesis for analyzing stress distribution in bone tissue and dental implants, as can be seen in Graphs E and F (Figs 6 and 7). This can be related to the possibility of using simplifications during FEA [23], because the farther the location of load application from the site of interest to be analyzed, the less influence the geometry will be evidenced [24], suggesting that the abutments and screws below the prostheses cannot behave similarly because they are very close to the loading.

Another observation is that a non-axial load applied on a cantilever arm presents a greater than double response on all stress generated in the anatomical prosthesis (Figs 6 and 7). These results suggest that failure of this rehabilitation system can be achieved much more quickly in this situation than when the same force is applied at the center of the model (Figs 6 and 7). Such higher stress values in the non-axial load corroborate with studies that analyzed the implant support arm of supported implants [25-27].

Tooth loss often affects several elements promoting a prosthetic space that can be rehabilitated with a fixed prosthesis. Currently, the literature is scarce regarding studies with multiple supported implants, which makes simplification a valid starting point for further studies.

5. Conclusion

Through this study, we conclude that:

• A simplified fixed prosthesis presents biomechanical behavior similar to a fixed anatomical prosthesis according to the stress distribution on bone tissue and implants;

• Also, when axial and non-axial loads are compared, the second one is more damaging to all components of a fixed prosthesis.

6.References

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2.2 Artigo – Tribst JPM, Rodrigues VA, Borges ALS, Nishioka RS. Efeitos biomecânicos de implantes dentários inclinados em uma prótese fixa parcial em cantilever através da análise por elementos finitos e extensometria in vitro / ***Biomechanical effects of inclined dental implants in a cantilever partial fixed prosthesis with finite element analysis and in vitro strain gauge****

RESUMO

Através do estudo da biomecânica de implantes dentários é que se torna possível compreender os efeitos da dissipação das cargas mastigatórias em diferentes situações e assim, prevenir a longevidade da osseointegração. O objetivo deste trabalho foi avaliar por extensometria (SGA) e análise por elementos finitos (FEA), as microdeformações geradas ao redor de implantes de hexágono externo (HE), sob a aplicação de cargas axiais e não axiais em uma prótese fixa de quatro elementos com implantes retos e inclinados em 17°. Através de um software CAD, foram modelados três implantes seguindo as medidas do fabricante. Em seguida, os implantes foram duplicados e divididos em dois grupos: um com implantes retos e respectivos pilares e outro, com implantes inclinados em 17° e respectivos pilares. Ambos grupos foram dispostos dentro de um bloco simulando tecido ósseo. Sobre os dois grupos, uma prótese fixa simplificada foi instalada e as geometrias foram exportadas para um software CAE de FEA. Cinco carregamentos de 300 N foram realizados em pontos axiais e não axiais sobre a prótese fixa e as tensões nos implantes e as deformações no bloco foram analisadas. Para validação do modelo utilizado, um experimento *in vitro* foi realizado seguindo todas estruturas confeccionadas na FEA. Em cada bloco experimental 4 extensômetros foram colados linearmente entre os implantes e os mesmos carregamentos foram repetidos através de um dispositivo aplicador de carga. As deformações computadas pela SGA foram correlacionadas com os resultados de FEA exibindo que o grupo com implantes inclinados possui comportamento biomecânico mais danoso e significantemente diferente do grupo com implantes retos ($P<0.005$). Em conclusão, o modelo matemático utilizado é um modelo válido e, os implantes inclinados podem induzir remodelações ósseas indesejadas.

Palavras-chave: Análise por elementos finitos. Extensometria. Implantes dentários.

ABSTRACT

Through the biomechanics study of dental implants, it is possible to understand the effects of dissipation of masticatory loads in different situations and prevent

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the longevity of osseointegration. The aim of this study was to evaluate the microstrains generated around external hexagon implants (HE), using axial and non-axial loads in a fixed four-element prosthesis with straight and inclined at 17 ° implants. Through CAD software, three implants were modeled following the manufacturer's measurements. Then, implants were duplicated and divided into two groups: one with straight implants and respective abutments and, the other with angled implants at 17 ° and respective abutments. Both groups were arranged inside a block simulating bone tissue. On both groups, a simplified fixed prosthesis was installed and the geometries were exported to CAE software. Five loads of 300N were performed at axial and non-axial points on the fixed prosthesis. Stress in the implants and strain in the block were analyzed. For validation of the model used, an in vitro experiment was performed following all structures made in FEA. In each experimental block, 4 strain gauges were placed linearly between the implants and the same loads were repeated with a loading applicator device. The deformations computed by the gauges were correlated with FEA's results showing that the group with inclined implants had biomechanical behavior more damaging and significantly different from the group with straight implants (P <0.005). In conclusion, the mathematical model used is a valid model and inclined implants can induce unwanted bone remodeling.

Keywords: Finite element analysis. Strain gauge. Dental implants.

1. Introduction

Based on the fundamental studies of Branemark et al. (1969)[1], and following a safe protocol of concepts, implant dentistry has established itself in modern dentistry as a tool of oral rehabilitation with reliable and safe results. In studying the longevity of the rehabilitative treatment, biomechanics has great importance in preventing already osseointegrated implant failure, since occlusal overload is one of the main causes of bone insertion loss around implants [2].

Bone structures have predictable behavior in front of a stimulus, as it has been defined that a normal mechanical stimulus results in preservation of bone tissue. Values considered low can lead to reabsorption due to disuse, and exacerbated values can lead to remodeling disorganization, which causes irreversible microstrain on the structure[3].

Several authors have studied the effect of the lever arm on implant prostheses and how this can influence the generated stresses[4-6]. Finite element analysis (FEA) was defined as a useful system to predict the behavior of these stresses[4-6]. However, a situation with inclined implants associated to a prosthetic lever has not been deeply studied in the literature yet.

In stress evaluation studies, the use of a bone tissue simulant material with the same mechanical behavior and capable of guaranteeing the system a reproducible pattern in all the specimens makes studies more concrete in providing inferences about the influence of the variables studied. In this context, polyurethane[7-10] is the material of choice due to its elasticity modulus and scientific validation.

Thus, correlating two numerical methodologies to study stress allows for a concise direction to interpret the results for possible elucidation of the clinical occurrence[11]. Therefore, the use of Strain Gauge as a complementary method to FEA can improve the interpretation of the results[11-13].

Finally, the objective of this study was to evaluate the microstrains generated around fixed four-element prosthesis with straight implants and implants inclined at 17°, under axial and non-axial loads, and to verify if they are at the physiological limit.

2. Methods

2.1 Tridimensional model

Using Rhinoceros software (version 6.0 SR8, McNeel North America, Seattle, WA, USA), an external hexagon implant (3.75 x 13 mm) (AS TECHNOLOGY TITANIUM FIX - São José dos Campos, Brazil) was modeled. The external hexagon platform was 0.7 mm high and 4.1 mm in diameter. Next, the model was replicated in order to obtain three identical implants with 3 mm distance between them. In the first group, the three implants were inserted without inclination, whereas the implants received a rotation of 17° for the second group.

After dividing the groups, a mini conical abutment was placed on each implant. For the group with straight implants, the abutments presented centralized insertion and 3 mm band. For the inclined group, the abutments were tapered at 17° (allowing for correction of the insertion trajectory during prosthesis installation) and 2.5 mm band.

Both groups were installed inside 3D-block models (95 x 45 x 20 mm) (Figure 1). An identical prosthesis for both groups was placed on the abutments (3 mm thick x 35 mm long x 15 mm wide). On the external surface of the fixed prosthesis, 5 circles of 2 mm diameter were demarcated to receive the load (Figure 2), corresponding to the center of the three retention screws (points A, B, C), 5 mm cantilever to point D, and 7 mm cantilever to point E.

2.2 FEA Processing

The dimensions were imported into Ansys software (ANSYS 16.0, ANSYS Inc., Houston, TX, USA). The material properties were assigned to each solid component as isotropic, homogeneous and linearly elastic. Young's modulus and Poisson's ratio of the materials were reported (Table 1) and all contacts were considered bonded.

2.3 Mesh Generation

A 10% convergence test determined 754,936 nodes with 440,893 elements for the straight group and 732,375 nodes with 428,219 elements for inclined group (Figure 3).

2.4 Loading and Fixations

The loading was performed in the upper region of the fixed prosthesis, exactly in the application circles with 2 mm in diameter (Figure 2).The location of the fixation was under the polyurethane block surface In all configurations, simulating the support of the sample on a plane. The applied load was 300N on Z axis.

2.5 Experimental Model

The experimental model followed the same dimensions for all components of the system, based on the theoretical model of regular geometries. For simulation of the bone tissue in the experimental model, two blocks (95 x 45 x 30 mm) of polyurethane (Polyurethane F160 Axson, Cercy - France) were obtained through a rectangular stainless steel metal matrix. After polymerization of the polyurethane, the blocks were removed from the matrix and had their surfaces polished with sandpapers (# 220 - # 600) (3M ESPE, St. Paul, USA) under water.

For implant installation in the polyurethane blocks, a set of milling cutters was used according to the manufacturer's recommendations (AS TECHNOLOGY TITANIUM FIX - São José dos Campos, Brazil). The matrices placed on the surface of the polyurethane following the methodology already used in other studies(8,17), serving as guides so that the implants were axially arranged and inclined at 17°. Three self-tapping implants of external hexagon measuring 3.75 in diameter by 13 mm in length (AS TECHNOLOGY TITANIUM FIX - São José dos Campos, Brazil) were installed in each block.Prosthetic abutments were installed on each implant with a torque of 20 Ncm with the aid of a manual torque wrench.

After placement of the implants and abutments, twenty fixed prostheses were cast in NiCr (n = 10).

2.6 Strain Gauge Installation

After careful cleaning of the blocks surfaces with isopropyl alcohol, four linear strain guages (KFG-1-120-C1-11L1M2R; KYOWA electronic instruments CO., Ltd., Tokyo, Japan, resistance 119.6 ± 0.4% Ω; gauge length: 1

mm; gauge factor: 2.08 ± 1.0%) were attached to each block with cyanoacrylate based adhesive (Super Bonder Loctite, São Paulo - Brazil). Two strain gauges were bonded to the proximal regions of the central implant and another two in the extremities, as shown in Figure 5. Evaluation of the resistance of each strain gauge was performed through a multimeter device (Minida ET 2055: Minida São Paulo - Brazil). Bonding of terminal plates was made in the upper surface of the block, where the electrical connections were adapted. Variations of electrical resistance were converted into microstrain-rate units through an electrical signal conditioning apparatus (Model 5100B Scanner - System 5000 - Instruments Division Measurements Group, Inc. Raleigh, North Carolina, USA, FAPESP proc: 07 / 53293-4). Electrical cables allowed the connection between the strain gauges and the data acquisition apparatus, where the acquisition channels were installed.

2.7 In vitro Load Aplication

Three static vertical loads of 300 N were performed[8,17] for each prosthesis (N=20) for 10 seconds on all 5 points on the prosthesis surface (Figure 2), similarl to what was done in the previous computational study.

2.8 Statistical Analysis

All the data obtained by the strain gauges were submitted to statistical analysis through MINITAB software (Minitab, version 17.3.0, 2016). One-way ANOVA was performed followed by Tukey test, with a significance level of 5%.

3. Results

The results obtained from the mathematical analysis followed maximum principal stress criteria for the non-ductile solids. As titanium is a friable material that fails by traction, the generated microstrains were evaluated for the block model.

The maximum stress found in the titanium implants during the different loads was expressed by the color scale in Figure 6.

The maximum strain found inside the blocks can be assessed with sagittal vision in Figure 7. The values around the implants exhibit a behavior pattern that is accentuated the farther the force is applied in relation to the central implant. Also, the system angulation aggravated the generated strains.

In the comparison between all the points of load application, the strain values around the implants were observed and are expressed in Figure 8.

The group inclined at 17° presented higher values of stress around the implants and the bone, especially when the load application was non-axial (Points D and E).

Data found on the blocks' surface were analyzed by four different points of measurement for Strain Gauge analysis of twenty samples (Figure 5). According to one-away ANOVA, the "implants inclination" factor was statistically significant ($p = 0.015$). Next, one graph with the mean values for strain gauges according to the bone's physiological limit was created (Figure 9, microstrain). One similar graph was created for correlating both methods and validating the mathematical model, thus presenting the equivalent strain by FEA methodology (Figure 9, equivalent strain).

In figure 9, it is possible to observe that the straight group and point B of the inclined group did not cross the physiological limit for both methods. Also, the graphs show that the stress peaks measured by FEA and Strain Gauge are not identical; however, they exhibit the same mechanical behavior.

4. Discussion

Stress distribution is an important factor that indicates the suitability of a fixed prosthesis and depends on the material properties and geometric configuration[18]. The use of prosthesis with inclined implants can influence the rehabilitation treatment's longevity.

The experiment results were statistically significant (Table 2) regarding the influence of using straight or inclined implants ($p = 0.015$), which corroborates with the results found by FEA when an increase in stress concentration is observed in the group with inclined implants on all load application points (Figure 6). As previously reported, there have been influences of different implant inclinations on the stress concentration through FEA[19-22] and Strain Gauge[21,23-24].

Verifications on stress distribution in implants have been carried out using the FEA method in many studies[19-22]. However, many of these models have not been validated and they can provide data that does not fit reality. FEA allows for absolute values and stress distribution. This methodology is an efficient, economical and accurate tool[18]. However, due to the use of an ideal situation in this method, an *in vitro* experiment is often necessary to confirm the obtained results[10,12-13].

The main methods used to verify the stress generated in experimental models are Photoelasticity, Strain Gauge and Digital Image Correlation. From the methods mentioned above, Strain Gauge is widely used in studies with implants and consecrated to obtain absolute values[10,18,13,23-26]. Strain gauges can be used in experimental trials to accurately measure surface parameters, but the measurement areas are strictly specific and unable to verify internal bone strain, which can be complemented by FEA[11-13]. The association of these methodologies can prevent some disadvantages and can speed up the clinical time[11].

Polyurethane has mechanical properties similar to human bone tissue (Table 1), which allows for quantitative verification of the implants' cervical region. This is different from Elsyad et al. (2016)[24] who used Strain Gauge in overdenture prostheses, but used acrylic resin as a substrate, only allowing for the qualitative results of inclined implants presenting higher stresses.

Measurement of generated numerical strain makes it possible to predict the maintenance of alveolar bone with tensions between 1000 - 1500 $\mu\varepsilon$, and that loads above 3000 $\mu\varepsilon$ will initiate a pathological reabsorption of the tissue[3,30-31]. Within this established physiological limit, the graph from Figure 7 is marked with a line (Physiological Limit) to show the situations that make the system clinically unfeasible.

As with any laboratory study to maintain the principle of reproducibility scientific methodology, Strain Gauge has limitations for the body in which the strain gauges are to be bonded. Thus, the use of an isotropic material validated in the literature as a substitute for bone tissue in laboratory studies was successfully employed in several studies[10,13,21,29-31]. The main difference between the correlation obtained through the methodologies under study and the literature is the use of the same bone simulant material in both methods. Using the same Young's modulus narrows down the differences between the methodologies, so that the same biomechanical behavior can be verified between all specimens. Several authors have compared the material of the experimental study with a three-dimensional model containing cortical and medullar bone[10,13,21,29-30]. In this way, they can be finding different values among methodologies that should find the same answer[21,29,30]. Similar to this study simulated by FEA in which a resin was used to fix the implants in the *in vitro* analysis, Wu et al. (2016)[13] used a resin substrate to simulate human bone tissue in the Strain Gauge analysis. Then, the authors also simulated the material in the analysis model using FEA, which guarantees better result precision.

Another way to guarantee significant results ($p<0.05$) was found by Eser et al. (2009)[12]. The authors used strain gauges attached to cadaver jaws and then simulated this tissue in FEA. However, using a resinous material is less complicated and is easier to reproduce by other researchers.

The results found in the present study showed that the inclined implants in a fixed prosthesis promotes more microstrain than the physiological bone maintenance limit. This is different from several authors that studied inclined unitary implants in the anterior region and did not find harmful strain values to bone tissue[19,21,32]. This may be related to the fact that the anterior region does not have a masticatory load as high as the posterior region, which causes the inserted teeth and implants to receive less force. In addition, the force applied in this region is oblique along the axis of the implant and is better balanced with angled abutments arranged opposing it.

It can be seen in Figure 6 that the stress pattern concentration in the implant body is very similar for both groups. However, when we observe the implants' platform in Figure 7, we can notice that the inclined group presents more traction and compression concentration with the same load in the straight implants. This can be explained by the fulcrum in the prosthesis being altered when the implants are inclined, suggesting that the force dissipation in non-axial components is more harmful.

The results of the present study at point C corroborate with the results found by Shimura et al. (2016)[10] who also used prosthesis on three implants and strain gauge. They evidenced that the mesial of the last implant had higher strain values than the distal of the same. This behavior means that when a non-centered force is applied to the prosthesis, a fulcrum forms at the implant closest to the compression point, and increases as more distal points are used (D and E), generating a greater rotation tendency of the prosthesis and further damage to the surrounding tissue. However, even at the most distal point of the present study, if the implants were ideally placed in the tissue, the values of the physiological limit for unwanted resorption were not reached; unlike the group with implants inclined at 17° where the unique load point which did not represent major problems was axial point B, exactly at the center of the prosthesis (Figure 7).

In Figure 8, the strain peaks occurred in the bone crest region, where the reabsorption and insertion loss of an already osseointegrated implant begins. The lowest strain value measured by both methodologies is when a fully axial force is applied at the center of the prosthesis, balancing the distribution throughout the system and maintaining the physiological limit. Similar to our study, several authors(10,17,33) found quantitatively higher stress values in the peri-implant bone when subjected to non-axial loads.

The results found in points D and E for both groups resemble studies that analyzed the lever arm of implants and found higher stress values around the last implant(4-5). However, for the group with three inclined implants, it would not be indicated to perform a fixed prosthesis, since applying fully axial loads would be impossible in the oral medium.

As FEA presented strains close to *in vitro* measurements, the FEA model was considered validated, corresponding to the *in vitro* experiment. The difference between FEA and strain gauge results may be due to strain gauge measurement errors, as settings reported in the FEA model, as well as the scoring areas in the FEA and the experiment are not exactly identical(5).

Regarding limitations of this study, the only items evaluated in these experiments were stresses on the implant bodies and the strain in the peri-implant bone. Other items can be checked to assess the inclination effects, such as splinting (or not) of the fixed prosthesis. In addition, the results found in this study may be employed in future studies addressing these limitations.

The present study aimed to verify the biomechanical effect of inclined implants' placement in the bone, and we created finite element analysis models and experimental models where the implants were actually placed. In this way, we can conclude that:

1. Strain and stress were significantly greater when inclined implants were used with any load application that is not fully centered;
2. The mathematical model used is valid for stress analysis in implants and bone strains.

Conflict of Interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Figures

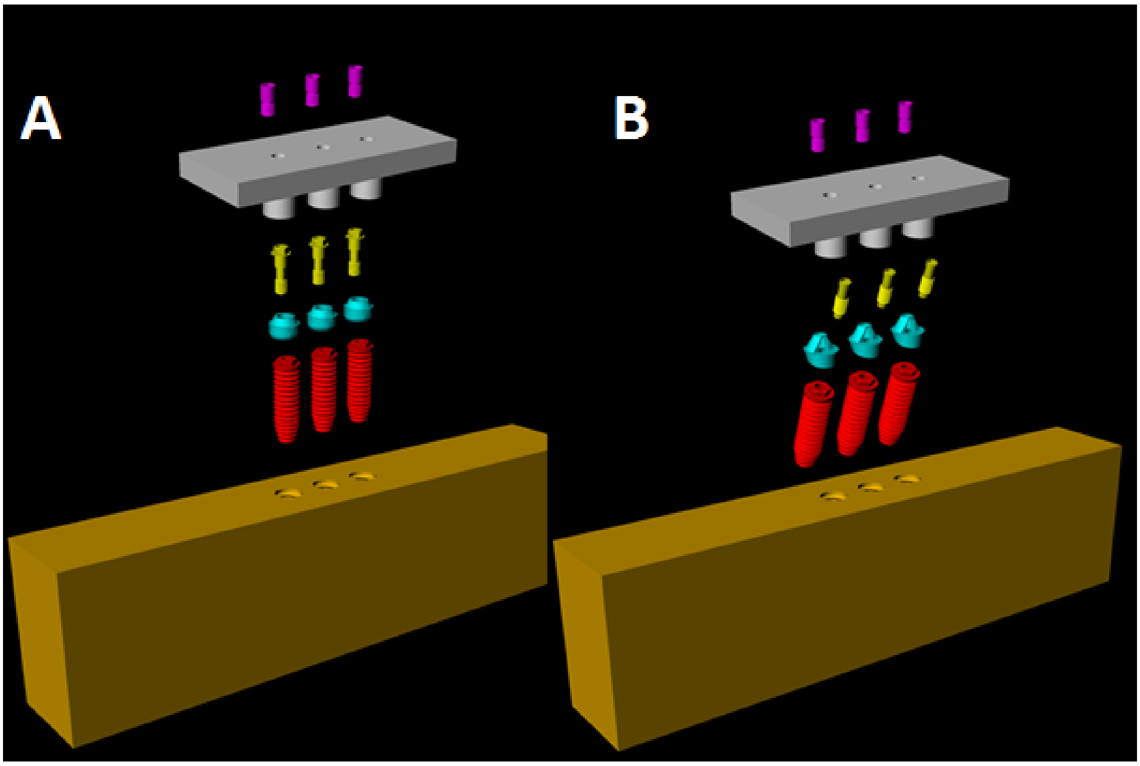


Figure 1: Final geometries according to the group: A) straight; B) inclined at 17 °.

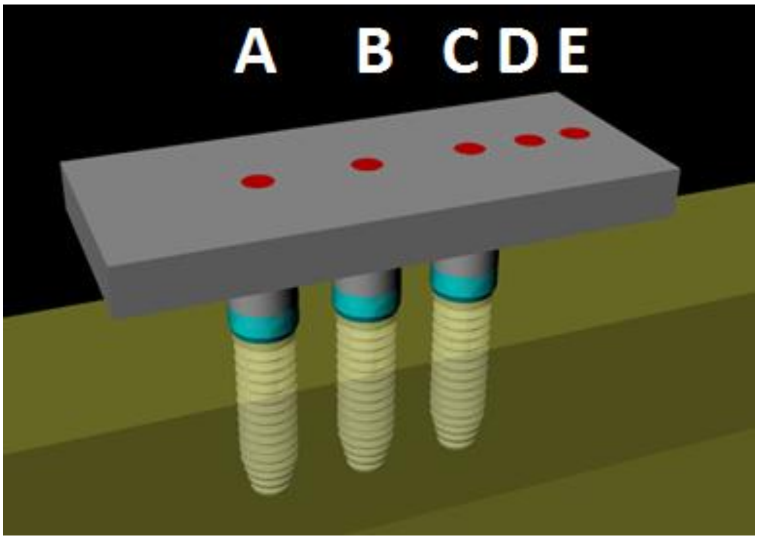


Figure 2: Delimited regions for load application.

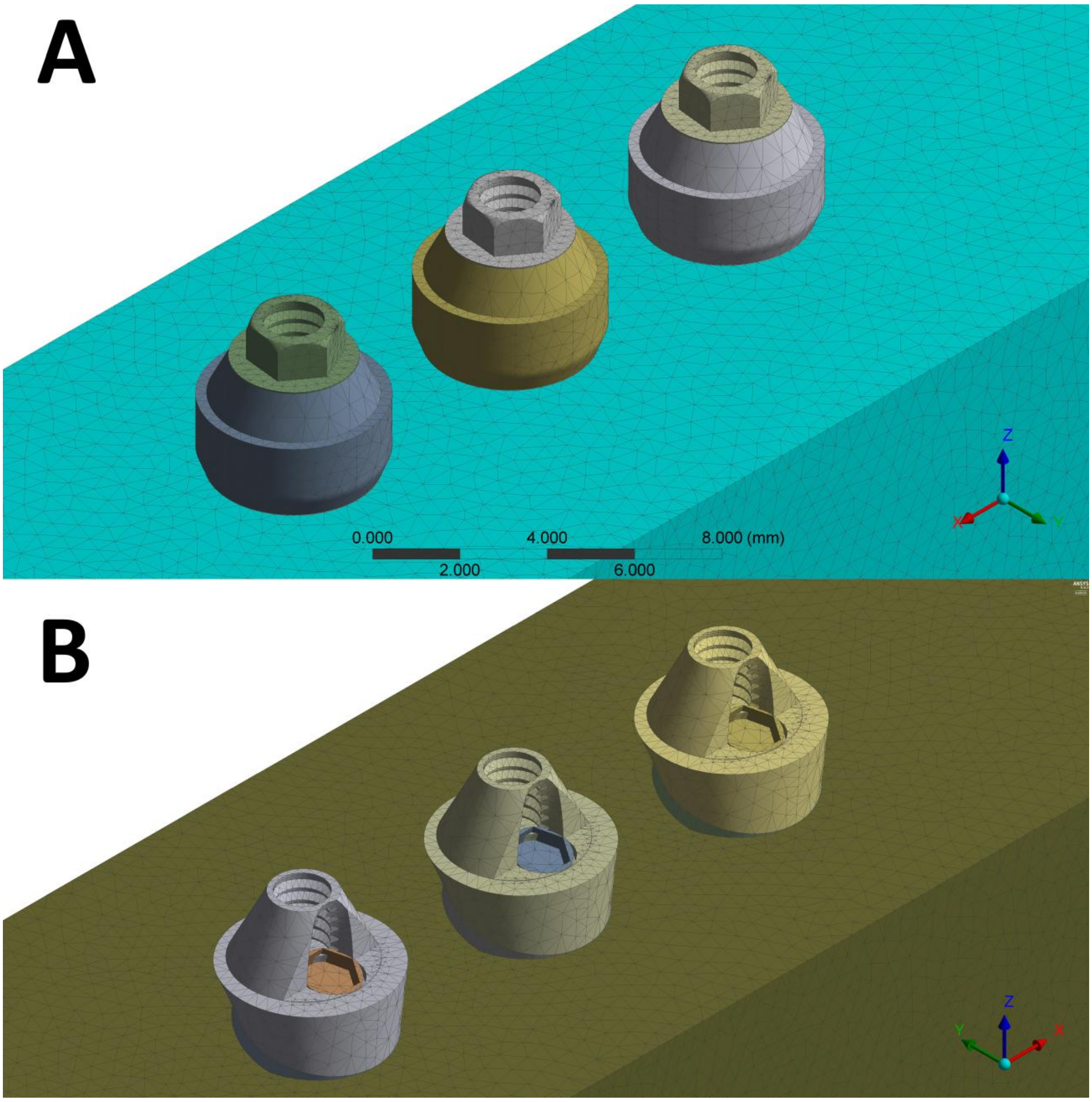


Figure 3: Mesh generated in the groups: A) with straight implants, B) with inclined implants.

Figure 4: A) Straight abutments for multiple prostheses on implants in polyurethane, B) Angled abutments for multiple prostheses on implants inclined in polyurethane.

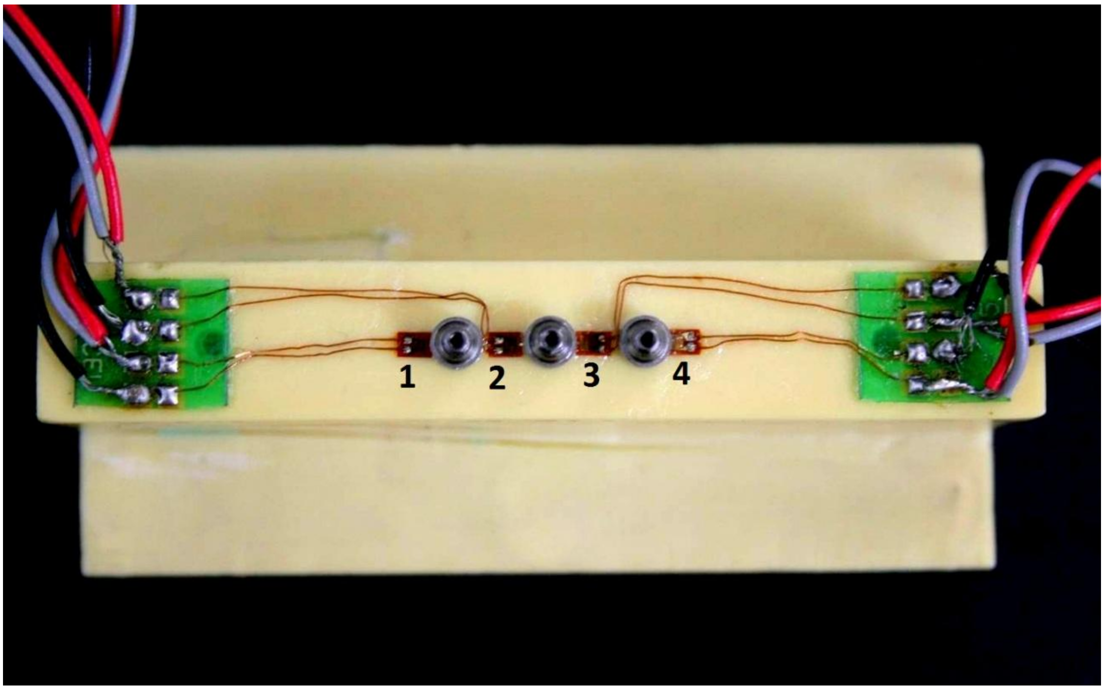


Figure 5: Strain Gauges linearly arranged between the abutments

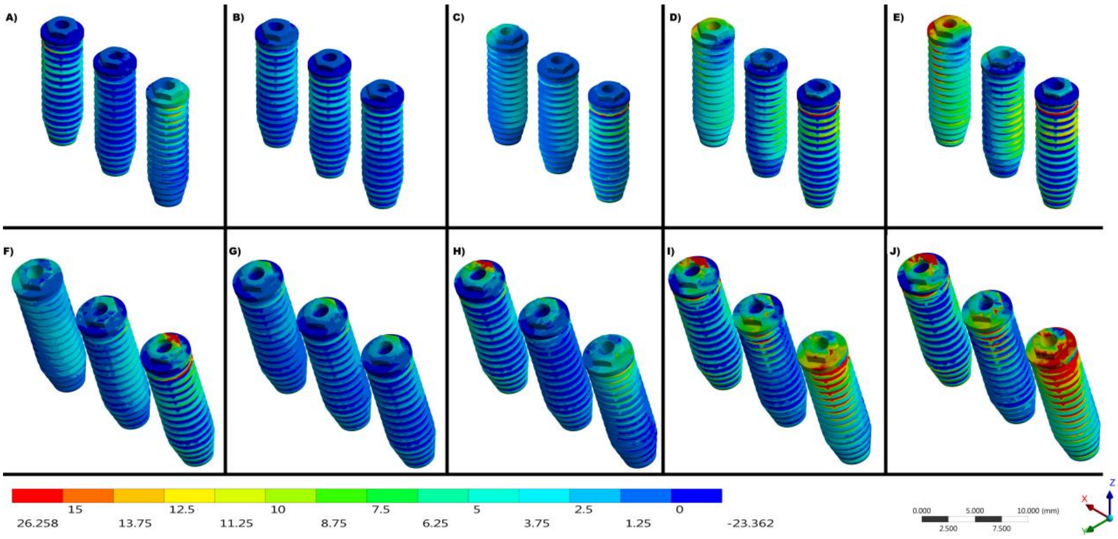


Figure 6: Maximum Principal Stress on implants under load aplications at points A, B, C, D and E, respectively. A-E) Straight Group and F-J) Inclined 17° Group.

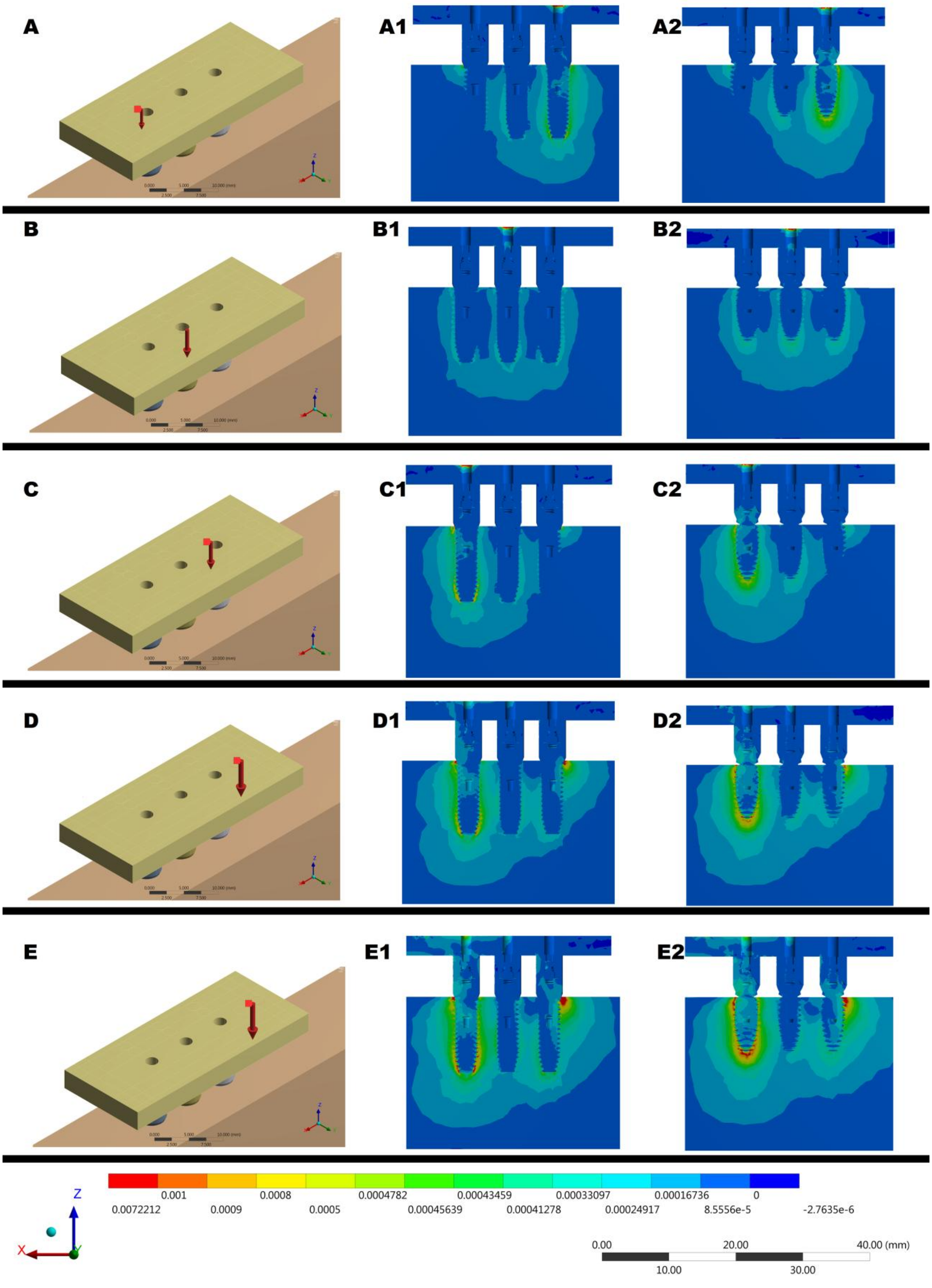


Figure 7: AE) From top to bottom, sequence of the application of load in the 5 different points and sagittal cuts of the interior of the block to evidence the maximum strain, with the figures of number 1 for the perpendicular group and 2, for the group in 17 °.

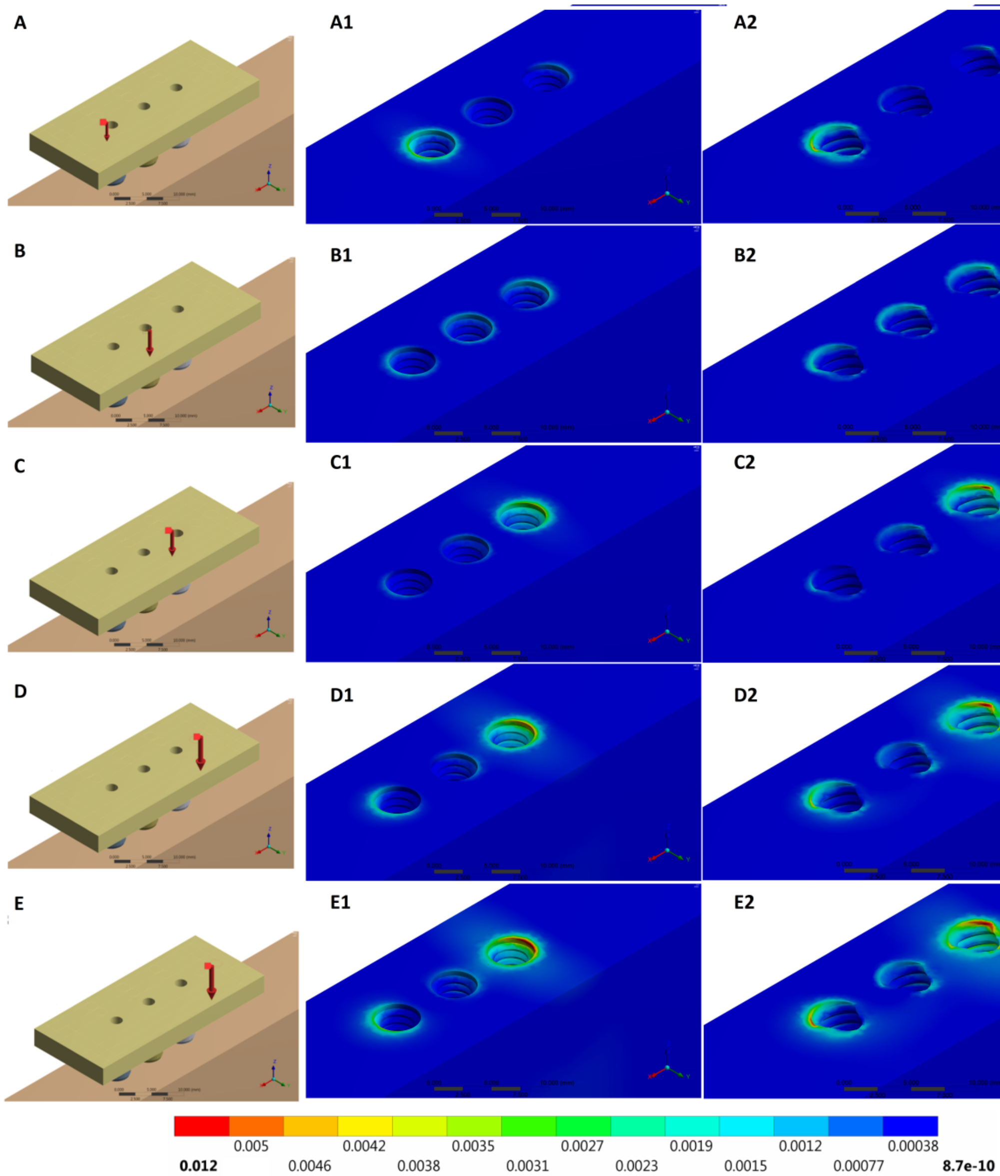
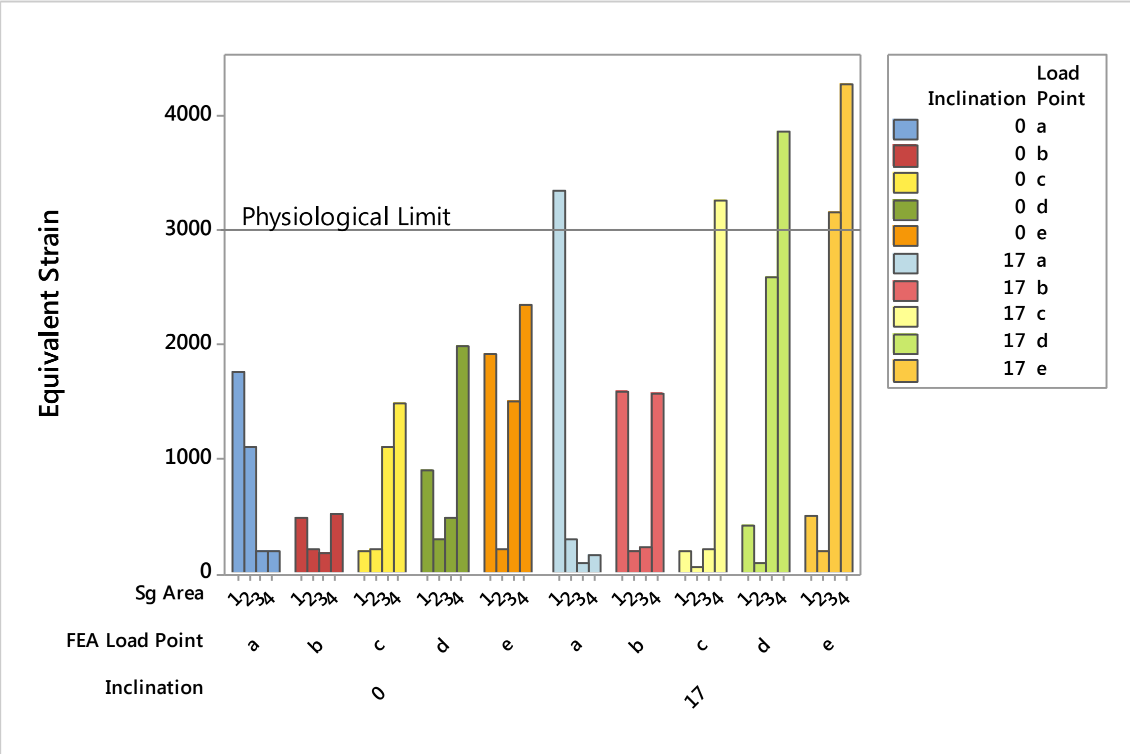


Figure 8: A-E) From top to bottom, sequence of the application of load in the 5 points on the surface of the specimen evidencing the equivalent strain, with the figures of number 1 for the straight group and 2, for the inclined 17 ° group.



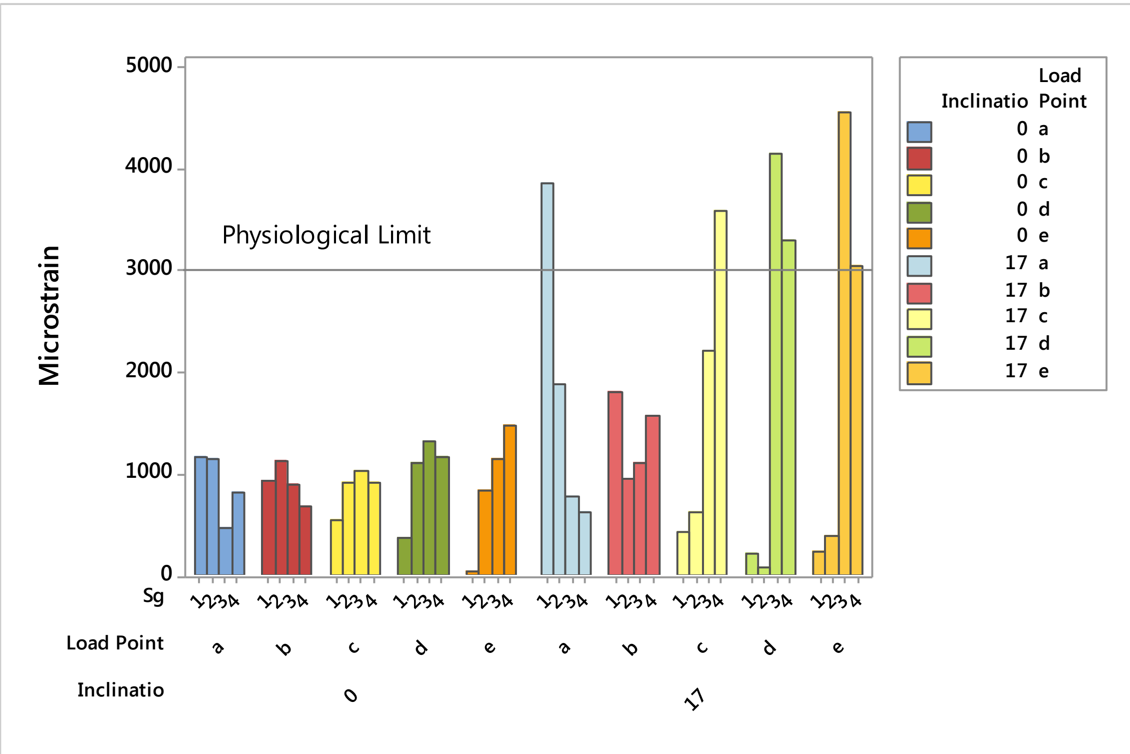


Figure 9: Bar graph of the strain generated in the *in silico* and *in vitro* experiment for both groups.

Tables:

Table 1 - Properties of the materials used in the study

Material	**Young Modulus**	**Poisson ratio**	**Reference**
Titanium	110 GPa	0.33	[14]
Nickel Chromium	206 GPa	0.31	[15]
Polyurethane	3.6 GPa	0.3	[16]

Table 2. ANOVA - 1 way of the strain values (με) in the *in vitro* experiment ($p<0.05$)

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Inclination	1	7491653	7491653	6,53	0,000
Error	38	43605438	1147512		
Total	39	51097090			

3 CONSIDERAÇÕES GERAIS

A disponibilidade de diversos componentes protéticos torna a implantodontia capaz de recuperar elementos perdidos mesmo nas situações mais adversas de disponibilidade óssea. Essa quantidade de variações possíveis para se alcançar o resultado da prótese em boca nem sempre segue critérios positivos para longevidade do tratamento, uma vez que dependendo do planejamento clínico estabelecido, a resposta biológica pode ser indesejada.

Das complicações presentes, o foco de nosso estudo aqui descrito se ateve a sobrecarga oclusal gerada pela dissipação agressiva das tensões compressivas, devido à influência de diferentes posicionamentos dos implantes. Principalmente porque a literatura já relata a influência de implantes inclinados com componentes corretores de angulação em situações unitárias ou em reabilitações totais, criando-se uma lacuna sobre as próteses-fixas parciais de vários elementos nessas condições.

Nesta linha de pesquisa, a análise por elementos finitos pôde viabilizar a utilização de uma prótese simplificada conforme descrito no primeiro artigo, e em termos de reprodutibilidade permitiu uma correlação precisa do comportamento *in vitro* e *in silico* na segunda parte do estudo.

Portanto, a partir dos resultados encontrados neste estudo, é possível contraindicar a instalação de implantes inclinados em 17°, mesmo que pilares corretores de angulação estejam corretamente utilizados. Tal recomendação contraria a maioria dos fabricantes de componentes protéticos, sendo um ponto de inovação de nosso estudo. No entanto, são necessários estudos com variações de apenas um ou dois implantes, materiais restauradores diferentes e até análises *in vivo* para definir de fato se esta indicação é viável ou não.

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