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Mechanical behavior of implant-supported full-arch prostheses in different locations in the maxilla: 3D-FEA and strain gauge analysis

Comportamento mecânico de próteses de arco inteiro implanto-suportadas em localizações diferentes na maxila: análise 3D-FEA e strain gauge

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ABSTRACT

The maxillary bone restriction can limit the implants position to support a full-arch prosthesis. **Objective:** Therefore, this study evaluated the biomechanical behavior of a full-arch prosthesis supported by six implants in different configurations: group A (implants inserted in the region of canines, first premolars and second molars), group B (implants inserted in the region of first premolar, first molar and second molar) and group C (implants in second premolar, first premolar and second molar). **Material and Methods:** The models were analyzed by the finite element method validated by strain gauge. Three types of loads were applied: in the central incisors, first premolars and second molars, obtaining results of von-Mises stress peaks and microstrain. All registered results reported higher stress concentration in the prosthesis of all groups, with group C presenting higher values in all structures when compared to A and B groups. The highest mean microstrain was also observed in group C (288.8 ± 225.2 $\mu\varepsilon/\mu\varepsilon$), however, there was no statistically significant difference between the evaluated groups. In both groups, regardless of the magnitude and direction of the load, the maximum von-Mises stresses recorded for implants and prosthesis displacements were lower in group A. **Conclusion:** It was concluded that an equidistant distribution of implants favors biomechanical behavior of full-arch prostheses supported by implants; and the placement of posterior implants seems to be a viable alternative to rehabilitate totally edentulous individuals.

KEYWORDS

Dental implants; Biomechanical phenomena; Dental prosthesis; Finite element analysis; Maxilla.

RESUMO

A limitação óssea maxilar totais pode limitar o posicionamento dos implantes para suportar uma prótese de arco total. **Objetivo:** Sendo assim, este estudo avaliou o comportamento biomecânico de uma prótese de arco total suportada por seis implantes em diferentes configurações: grupo A (implantes inseridos na região de caninos, primeiros pré-molares e segundos molares), grupo B (implantes inseridos na região de primeiro pré-molar, primeiro molar e segundo molar) e grupo C (implantes em segundo pré-molar, primeiro pré-molar e segundo molar). **Materiais e métodos:** Os modelos foram analisados pelo método de elementos finitos validados por extensometria. Foram aplicados três tipos de cargas: nos incisivos centrais, primeiros pré-molares e nos segundos molares, obtendo resultados de picos de tensão de von-Mises e microdeformação. Todos os resultados registrados mostraram maior concentração de tensão na prótese de todos os grupos, sendo que o grupo C apresentou maiores valores em todas as estruturas quando comparado com os grupos A e B. A maior média de microdeformação também foi observada no grupo C (288,8 ± 225,2 $\mu\varepsilon/\mu\varepsilon$), no entanto, não houve diferença estatisticamente significativa entre os grupos avaliados. Em todos os grupos, independentemente da magnitude e direção da carga, as tensões máximas de von-Mises registradas para os implantes e deslocamentos de próteses foram menores no grupo A. **Conclusão:** Concluiu-se que a distribuição de implantes de forma equidistante favorece o desempenho biomecânico das próteses de arco total suportada por implantes; e o posicionamento de implantes posteriores parece ser uma alternativa viável para reabilitar indivíduos densdentados totais.

PALAVRAS-CHAVE

Implantes dentários; Fenômenos biomecânicos; Prótese dentária;, Análise de elementos finitos; Maxila.

INTRODUCTION

Implants with external hexagon-type connections presents biomechanical characteristics with acceptable immediate performance as well as in the long-term follow-up. For this and other reasons, fixed prostheses on external hexagon implants are a very popular option in the treatment of edentulous patients [1].

However, for rehabilitation with an implant-supported restoration, it is necessary to have adequate bone remnant to support the masticatory loads. After tooth extraction or tooth loss, the alveolar bone undergoes a physiological remodeling process that often limits the amount of bone, especially in the anterior region of the maxilla; dampening the oral rehabilitation in this region [2]. Thus, there are two major clinical procedures that can provide the necessary anchorage in these areas: bone grafting or the use of long implants in the posterior region with anchorage in other portions of the bone tissue [3]. It is important to emphasize that the use of long implants with zygomatic anchorage, in addition to being invasive and requiring hospitalization, usually has a high cost to the patient [4].

A clinical option that overcomes these limitations would be the implant placement in the posterior region of the maxilla. However, this treatment option can present complications in the long-term due to the lack of standardization of it and mechanical studies supporting its indication [5]. The two major factors of implant failure are: peri-implantitis and occlusal overload. Both factors can act together or independently and cause peri-implant marginal bone loss that, in advanced cases, can lead to implant loss [6,7].

When the chewing loading mechanical stimuli are within physiological limits, they will result in the maintenance of the bone level, however, when the stimuli exceed the physiological limits, the consequence is a bone loss caused by the disorganization of the remodeling process [8]. Therefore, to avoid the marginal bone loss, it is of great importance to know how the masticatory loads can modify the biomechanical behavior of implant prosthesis [9], since the condition of the marginal bone of an implant in function is influenced by transmitted occlusal forces to him [10].

Axial loads transmit stresses along to the implant axis more homogeneously than oblique loads, being considered more friendly by the peri-implant bone tissues [11,12]. However, the positioning of implants and the framework of a prosthesis on implants can influence the distribution of occlusal loads and result in a greater presence of oblique loads, which intensify the magnitude of stresses transferred to the marginal bone [13]. In order to improve the understanding of the biomechanical behavior of fixed prostheses on implants, in vitro and in silico studies have been used through bioengineering tools, such as the numerical analysis using the finite element methods [14].

Finite element method allows simulating the possible stresses in the theoretical model. This methodology has the advantage of allowing simulation of various well-controlled conditions, allowing the analysis of the biomechanical behavior of implants in areas of difficult clinical access [15]. However, it can give more reliable results when associated with in-vitro methods such as strain gauge analysis. Therefore, this research aimed to evaluate the stress and strain distribution of implant-supported full-arch prostheses with different implant configurations and load conditions. The null hypothesis was that the microstrains would be similar regardless the simulated condition.

MATERIAL AND METHODS

3D modelling

The external hexagon implant and prosthetic screw were created according to the manufacturer's dimensions (Intraoss, Sistemas de Implantes, Itaquaquecetuba, SP, Brazil) using Computer- Aided-Design (CAD) software (Rhinoceros 5.4.2, SR8, McNeel North America, Seattle, WA, USA). To design the maxillary and prosthesis' 3D model, a real polyurethane maxilla model and prothesis were digitalized (Scanner trios 3, open format in STL) allowing the acquisition of the stereolithography (.STL) file.

After that, the computational analysis was performed simulating this reference model in three groups with different configurations of implant placement and transferred to a CAD software for the elaboration of the volumetric model.

The STL file was converted using the Rhinoceros software (version 5.4.2 SR8, McNeel North America, Seattle, WA, USA), using reverse engineering tool. The fixed prosthesis on the implants were modeled with the same steps as the maxilla from the STL file generated by the CAD software. After, the 3D model was finally finished as a volumetric model (Figure 1).

Boundary conditions

After modelling, the three-dimensional model was imported into Ansys software (ANSYS 16.0, ANSYS Inc., Houston, TX, USA) in order to carry out a static structural analysis. Material properties were used from software database. The geometries were renamed according to what they are representing, and all structures were considered linear, homogeneous, isotropic and elastic. After checking the contact between the structures, they are considered bonded and the number of faces tangent between two solids were adjusted with similar quantity (Figure 2).

The meshing process has been carried out automatically, in which the software allowed the refinement of the mesh created using tetrahedral elements.

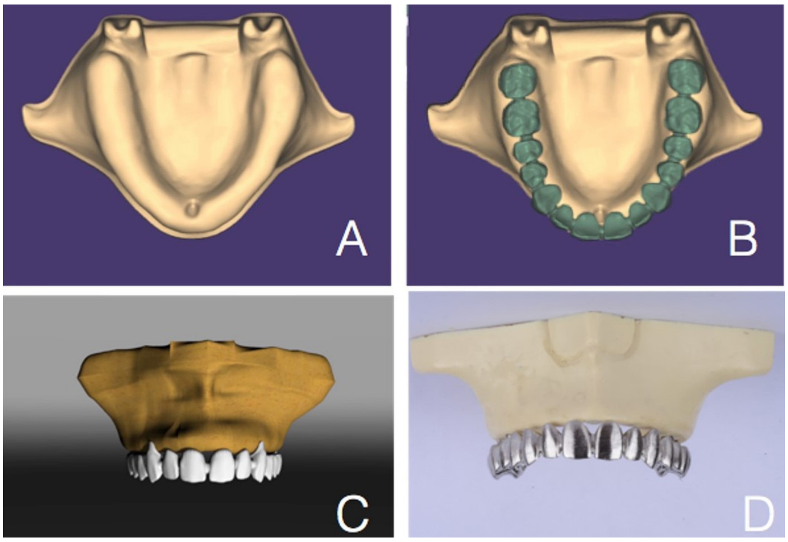

Figure 1 - (A) Model generated based on the external geometry of the pre-existing model; (B) Implant-supported prosthesis designed in CAD software; (C) Model was transformed into a volumetric solid; (D) Pre-existing physical model that served as the basis for the digital archives and for the in-vitro strain measurement.

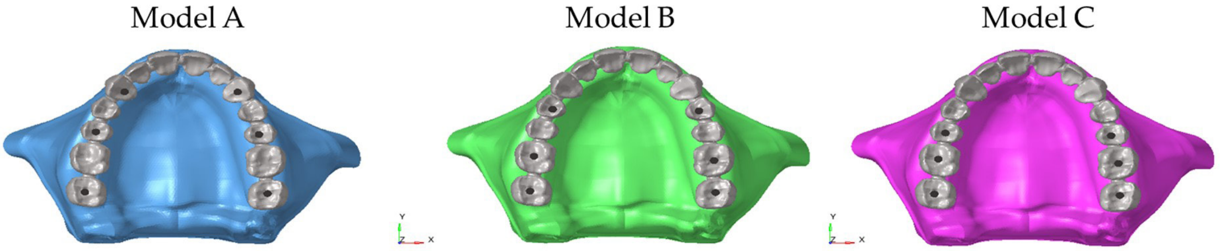

Figure 2 - Model A: implants inserted in the region of canines, first premolars and second molars. Model B: implants inserted in the region of the first premolar, first molar and second molar. Model C: implants inserted in the region of second premolar, first premolar and second molar.

For each load (axial and non-axial) an analysis configuration was used. For all configurations, the maxilla was fixed on its lower external surface simulating the support of the model in a plane. Load was defined as vector in the Z-axis direction with 300N force on premolars and molars, 100N on maxillary central incisors. After the simulations, von-Mises stress solutions were conducted for the implants, prosthetic screws and the maxillary model for each load (Figure 3).

In-vitro strain assessment

To validate the FEA model an in-vitro model was design with similar conditions. The surfaces of the model were prepared and cleaned with isopropyl alcohol and electric linear strain gauges (KFG-02-120-C1-11, Excel Sensores Industria e Comercio., Ltd –Taboão da Serra– SP, Brazil) were bonded. Each sensor was positioned close to the implant using a transparent adhesive tape and a cyanoacrylate-based adhesive (Super Bonder Loctite, São Paulo – Brazil).

The model received similar loads following FEA with a 2 mm diameter rounded tip as the load application device [16]. Variations in electrical resistance were transformed into microstrain units using an electrical signal conditioning device (Model 5100B Scanner – System 5000 – Instruments Division Measurements Group, Inc. Raleigh, North Carolina – USA, FAPESP proc: 07/53293-4). Data recording was performed using strain-smart software. Electrical cables allowed the connection between the strain gauges and the data acquisition device (Figure 4).

It was possible to observe for each image that the hot colors represent the zones with the highest stress concentration (von-Mises Stress), that is, regions under higher stress and for each analyzed structure.

RESULTS

The implant-supported prosthesis was the structure with the highest stress peak for the three groups, which could be observed that in the region of the most mesial implants. However, the maxillary model did not show a high magnitude of stress regardless the different conditions, in addition to the mesial region of the first implant (figures 5-7) (Table I).

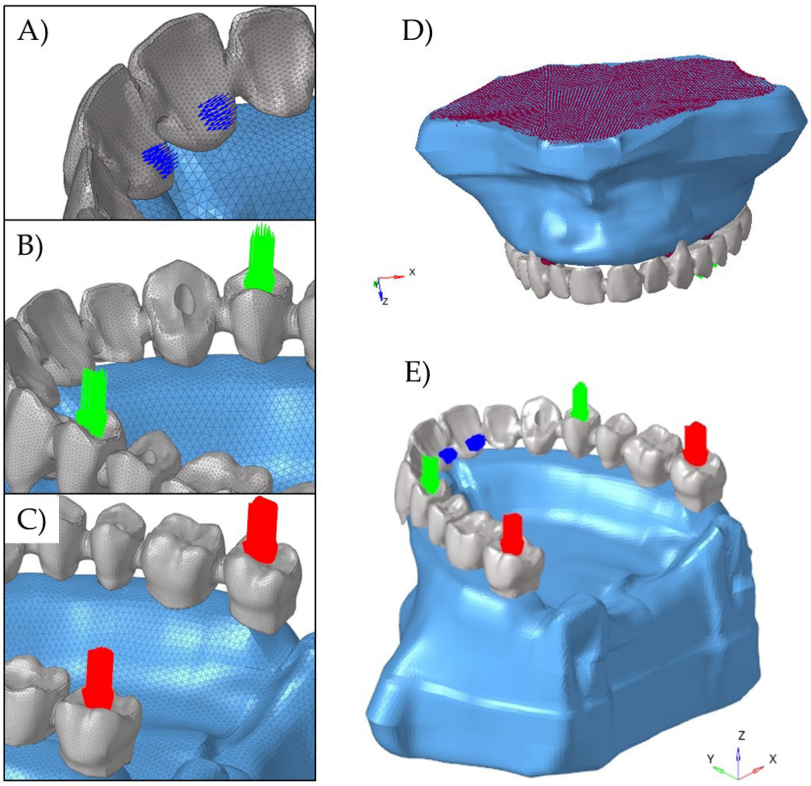

Figure 3 - Loading simulation: (A) Oblique loading in central incisors; (B) simulation of axial loading in first premolars; (C) axial loading on second molars; (D) model fixation for load application and, (E) perspective view of the different loading conditions.

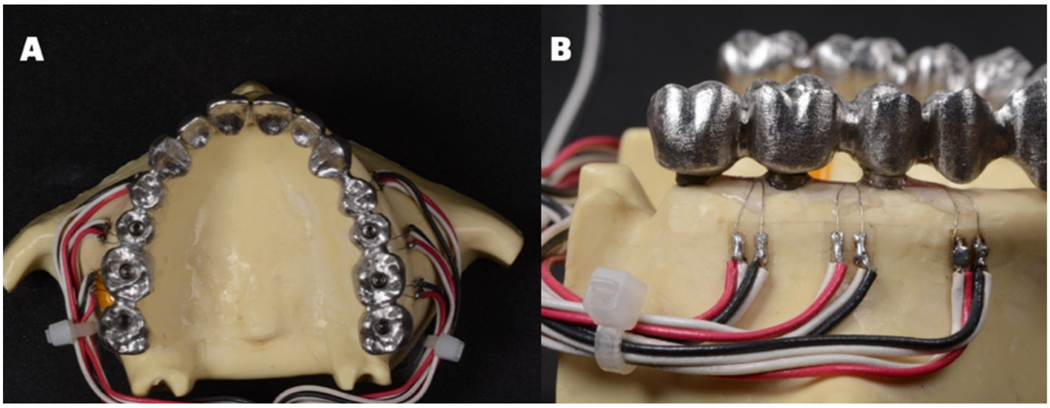

Figure 4 - Model with strain gauges bonded in the model surface. Occlusal view (A) and lateral view detailing the position each sensor (B).

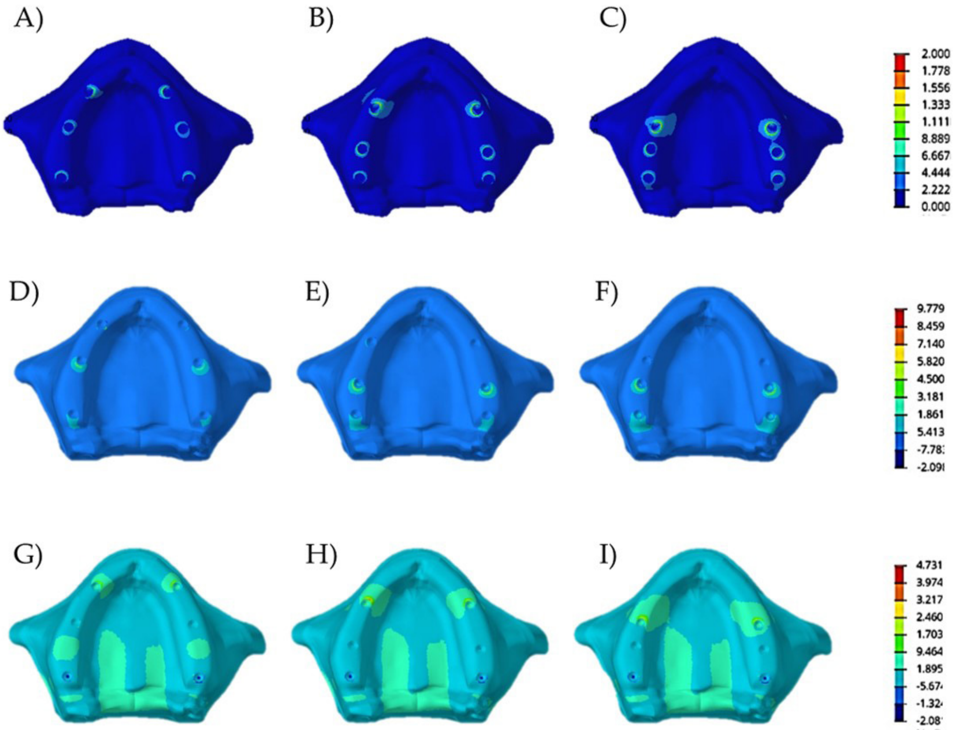

Figure 5 - Von-Mises Stress (MPa) results in the bone tissue for loading in central incisors (A-C), in the first premolars (D-F) and upper molars (G-I) according to the three different models.

Table I - Stress peaks (MPa) calculated according the different models (A, B and C) as well as the loading region for each of the evaluated structure

Structure	Loading condition	Model A	Model B	Model C
Maxilla	Incisor	44	13	65
	Pre molars	47	50	68
	Molars	47	23	94
Implant	Incisor	31	68	61
	Pre molars	43	47	77
	Molars	55	96	151
Screw	Incisor	57	96	68
	Pre molars	65	65	102
	Molars	74	133	253
Prosthesis	Incisor	77	99	128
	Pre molars	98	150	159
	Molars	87	168	441

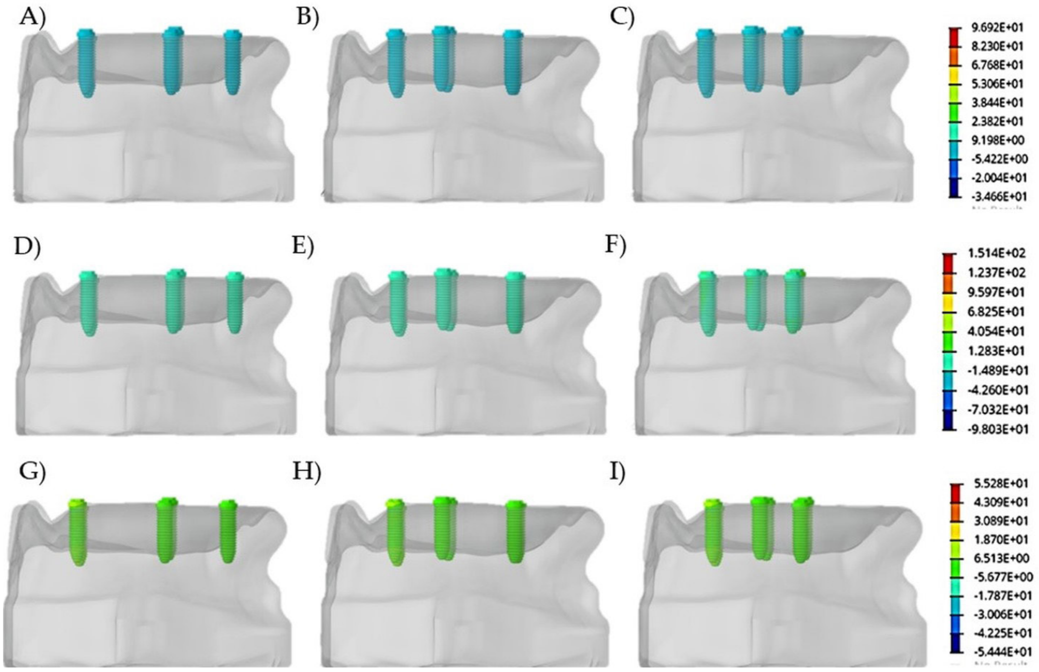

Figure 6 - Von-Mises Stress (MPa) results in the dental implant for loading in central incisors (A-C), in the first premolars (D-F) and upper molars (G-I) according to the three different models.

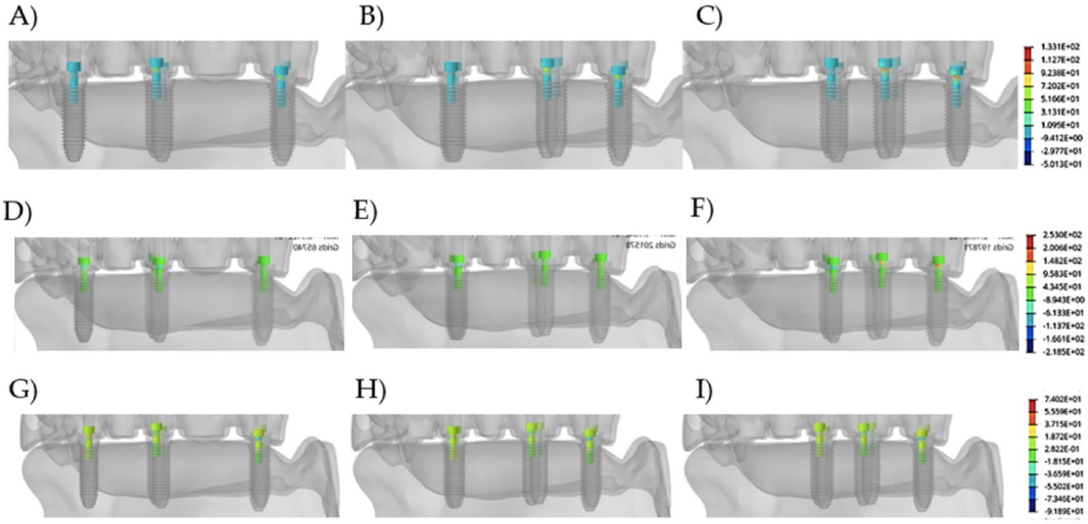

Figure 7 - Von-Mises Stress (MPa) results in the prosthetic screw for loading in central incisors (A-C), the first premolars (D-F) and upper molars (G-I) according to the three different models.

Therefore, for the oblique loads applications, it was possible to observe a lower concentration of stress and deformation in the structures furthest from the loading regions and higher stresses in the regions closer to the load application point. When the load was applied in a region of the first molar of the prosthesis, the stresses were distributed more homogeneously between the evaluated structures.

Observing the deformation distribution generated in group C, it is possible to notice that the magnitude of the deformation peak is concentrated in the more mesial implants when the load applied to the centrals compared to groups A and B.

For strain gauge analysis, statistical tests were performed using the R-project 3.2.0 software (Table II). The significance level established for

Table II - Strain peaks (microstrain) calculated according the different models (A, B and C) as well as the loading region (Incisors, Pre molars and Molars) for each of strain gauge

Group	Loading condition	Guage 1	Guage 2	Guage 3	Guage 4	Guage 5	Guage 6
Group A	Incisor	40.7	-30.6	-90.1	-88.2	-28.4	65
	Pre molars	47	124	-8.7	-7.6	116.3	68
	Molars	190.2	40.4	20	18.7	47.1	186.9
Group B	Incisor	-9.7	24.8	-390.1	-377.8	27.1	-10.2
	Pre molars	70.4	110.2	-160.4	-158.7	109.5	68.2
	Molars	180.7	49.6	349.2	352.5	52.3	174.3
Group C	Incisor	-18.1	31.4	-514.4	-502.7	28.3	-21.2
	Pre molars	96.5	120.1	-181.2	-176.3	125.2	89.4
	Molars	201.5	59.4	390.7	402.6	48.3	190.3

Table III. Kruskal-Wallis table according to each model

Model	με/με (dp)	X^2	df	p-value
A	241.2±178.9	0.205	2	0.902
B	258.8± 201.4			
C	288.8±225.2			

the tests was equal to 5%, which established a 95% confidence interval for the presented results (Table III). Therefore with similar mechanical behavior between in-vitro strain peaks and theoretical stress peaks, the model has been considered validated.

With values of $p < 0.05$ for the Shapiro-Wilk test, the distribution of deformations (Strain) was considered non-normal. Kruskal-Wallis statistical test was applied to assess the relationship between each model and its strains. The results obtained showed no statistical difference ($p = 0.902$) for the evaluated groups when considering the average strain per model (Table III).

For each load application point, the Kruskal-Wallis test and Dunn's multiple comparison test were used. It was possible to observe that there was no statistical difference for the different loading conditions ($X2 = 2.486$, $df = 5$, $p = 0.778$).

DISCUSSION

This study evaluated the influence on external hexagon implants in three different designs of multiple implant-supported prostheses in edentulous maxilla. The null hypothesis was partially accepted since the microstrain were similar between the groups. However, it was also possible to observe that the greater the lever arm in the anterior region, the greater the magnitude of the stresses calculated for the implants and structures of the prosthetic system.

According to the literature [17], in silico methods such as finite element analysis, can be used to measure bone behavior. The use of such 3D method requires prior knowledge of bone volume and mechanical properties. However, the bone tissue is not homogeneous and its physical properties vary greatly according to species, age, sex, type of bone (e.g., femoral, mandibular, cortical, cancellous) and even according to location of the bone from which the sample was taken [18,19].

Therefore, studies with human bone have a complexity and heterogeneity and, for ethical reasons, often delay the development of clinical trials. Thus, through an in vitro study, a previous study evaluated the elastic modulus of an experimental polyurethane isotropic model, by means of stress tests and compared the results with those reported in the literature with bone [19,20]. According to them, the use of the polyurethane model in place of bone in in vitro biomechanical studies is a validated method. Based on that, the present study used the in vitro polyurethane model and simulated the numerical model with the properties of this isotropic model.

In the present results, the disposition of the implants to distal in the edentulous maxilla caused a higher stress concentration for the analyzed structures, in accordance with previous studies that reported a similar behavior, when the distance between the implants increased [21-23]. A previous study [24] reported that implants installed respecting the minimum space between each implant (3 mm) demonstrated a better mechanical response of the bone tissue to masticatory loads. In this way, the use of six adjacent implants in the posterior region (Group C) allowed an acceptable mechanical behavior of the peri-implant bone under load. Therefore, the results obtained for the different implant positions clearly indicated that the stress was lower in model A compared to other models B and C.

The stress in the implant and in the framework increased as the implants were installed distally to the molar region. Therefore, the more distal the configuration of the implants, the greater the distance between the anterior abutments of the implant. When the load was on the central incisors, the amount of stress concentration were visibly higher compared to the similar loading condition in model A. This finding is consistent with the study of previous authors [25], who found that cantilever loading had a large effect on stress concentration. Increased stress can increase the risk of treatment failure [12]. The results obtained in the present study also indicated that anterior cantilever can negatively affect the implant stress magnitude.

Although the positions of implants B and C can be considered almost similar, the loading on the central incisors increased the stress on the mesial implant in group C compared to group B, showing that these designs present different mechanical response.

Another novelty of the present study in relation to previous reports in the literature was the verification of stress, considering a cantilever prosthesis in the anterior maxillary implants. Although this factor has been evaluated in previous studies [12,21-26], there is lack of information when considering different implant positions. The literature [21-27] usually reports the maximum forces capable of generating mechanical problems in the bone-implant interface, however, there are no reports showing the cantilever in anterior region.

It is noteworthy that this study was subject to some limitations, as the loading condition was simplified [28-30]. Axial loads transmit stresses along the axis of the implant in a more homogeneous way, being better accepted by the peri-implant bone tissues [31,32]. However, the positioning of the implants and the framework of a prosthesis on implants can influence the distribution of occlusal loads and result in a greater amount of oblique loads, which intensify the magnitude of the stresses transferred to the marginal bone [33]. In order to improve the understanding of the biomechanical behavior of fixed prostheses on implants, in vitro and in silico studies have gained notoriety through bioengineering tools, such as, for example, analyzes by FEA and strain gauge [30-33].

Future studies should apply different bone densities, anatomical structures such as the maxillary sinus and diversify the size and angulations of implants for this situation. Furthermore, although the experimental models were rigorously prepared and experienced dentists were involved in all procedures, the bone model is still an isotropic structure that is limited in terms of mechanical response. Therefore, it is not recommended to extrapolate these results to implant-supported prostheses in clinical situations, and further studies should be carried out to assess the effect of traction forces on the biomechanics of these prostheses. However, despite all the limitations, the present results can be used to guide further in-vitro studies and to elucidate how the implants distribution and loading condition can modify the mechanical behavior of the full-arch prothesis on implants.

CONCLUSIONS

According with the obtained results and model validation it is possible to conclude that the implants inserted in the region of canines, first premolars and second molars showed the most promising mechanical behavior, while the distal implants placement showed the highest stress. However, the positioning of implants in the posterior region of the maxilla seems to be a viable alternative to rehabilitate edentulous maxilla.

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Author's Contributions

MFBG: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization, Supervision, Project Administration and Funding Acquisition. GRSL: Conceptualization, Methodology, Validation, Formal Analysis, Writing – Original Draft Preparation. MLT: Formal Analysis. AAP: Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft Preparation. JDMM: Resources, Writing – Original Draft Preparation. RSN: Conceptualization, Writing – Original Draft Preparation, Writing – Review & Editing, Visualization, Supervision, Project Administration and Funding Acquisition.

Conflict of Interest

The authors declare no conflict of interest.

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Regulatory Statement

This study was conducted in accordance with all the provisions of the local human subjects oversight committee guidelines and policies.

REFERENCES

1. Misch CE, Suzuki JB, Misch-Dietsh FM, Bidez MW. A positive correlation between occlusal trauma and peri-implant bone loss: literature support. Implant Dent. 2005;14(2):108-16. http://dx.doi.org/10.1097/01.id.0000165033.34294.db. PMid:15968181.
2. Andrade GS, Kalman L, Giudice RL, Adolfi D, Feilzer AJ, Tribst JP. Biomechanics of implant-supported restorations. Braz Dent Sci. 2023;26(1):e3637. http://dx.doi.org/10.4322/bds.2023.e3637.
3. Kizhakedathil MPJ, C SD. Acid stable α-amylase from *Pseudomonas balearica* VITPS19-Production, purification and characterization. Biotechnol Rep (Amst). 2021;30:e00603. http://dx.doi.org/10.1016/j.btre.2021.e00603. PMid:33747801.
4. Davó R, Bankauskas S, Laurincikas R, Koçyigit ID, Mate Sanchez de Val JE. Clinical performance of zygomatic implants-retrospective multicenter study. J Clin Med. 2020;9(2):480. http://dx.doi.org/10.3390/jcm9020480. PMid:32050501.
5. Kreissl ME, Gerds T, Muche R, Heydecke G, Strub JR. Technical complications of implant-supported fixed partial dentures in partially edentulous cases after an average observation period of 5 years. Clin Oral Implants Res. 2007;18(6):720-6. http://dx.doi.org/10.1111/j.1600-0501.2007.01414.x. PMid:17888017.
6. Lindhe J, Meyle J, Group D of European Workshop on Periodontology. Peri-implant diseases: Consensus Report of the Sixth European Workshop on Periodontology. J Clin Periodontol. 2008;35(8, Suppl):282-5. http://dx.doi.org/10.1111/j.1600-051X.2008.01283.x. PMid:18724855.
7. Malchiodi L, Cucchi A, Ghensi P, Consonni D, Nocini PF. Influence of crown-implant ratio on implant success rates and crestal bone levels: a 36-month follow-up prospective study. Clin Oral Implants Res. 2014;25(2):240-51. http://dx.doi.org/10.1111/clr.12105. PMid:23402530.
8. Frost HM. Wolff's Law and bone's structural adaptations to mechanical usage: an overview for clinicians. Angle Orthod. 1994;64(3):175-88. PMid:8060014.
9. Kayumi S, Takayama Y, Yokoyama A, Ueda N. Effect of bite force in occlusal adjustment of dental implants on the distribution of occlusal pressure: comparison among three bite forces in occlusal adjustment. Int J Implant Dent. 2015;1(1):14. http://dx.doi.org/10.1186/s40729-015-0014-2. PMid:27747636.
10. Tribst JPM, Dal Piva AMO, Borges ALS, Rodrigues VA, Bottino MA, Kleverlaan CJ. Does the prosthesis weight matter? 3D finite element analysis of a fixed implant-supported prosthesis at different weights and implant numbers. J Adv Prosthodont. 2020;12(2):67-74. http://dx.doi.org/10.4047/jap.2020.12.2.67. PMid:32377319.
11. Sahin S, Cehreli MC, Yalçin E. The influence of functional forces on the biomechanics of implant-supported prostheses--a review. J Dent. 2002;30(7-8):271-82. http://dx.doi.org/10.1016/S0300-5712(02)00065-9. PMid:12554107.
12. Sahin S, Cehreli MC, Yalçin E. The influence of functional forces on the biomechanics of implant-supported prostheses--a review. J Dent. 2002;30(7-8):271-82. http://dx.doi.org/10.1016/S0300-5712(02)00065-9. PMid:12554107.
13. Datte CE, Tribst JP, Dal Piva AO, Nishioka RS, Bottino MA, Evangelhista AM, et al. Influence of different restorative materials on the stress distribution in dental implants. J Clin Exp Dent. 2018;10(5):e439-44. http://dx.doi.org/10.4317/jced.54554. PMid:29849967.
14. Farah JW, Craig RG, Sikarskie DL. Photoelastic and finite element stress analysis of a restored axisymmetric first molar. J Biomech. 1973;6(5):511-20. http://dx.doi.org/10.1016/0021-9290(73)90009-2. PMid:4748499.
15. Tribst JPM, Dal Piva AMO, Lo Giudice R, Borges ALS, Bottino MA, Epifania E, et al. The influence of custom-milled framework design for an implant-supported full-arch fixed dental prosthesis: 3D-FEA sudy. Int J Environ Res Public Health. 2020;17(11):4040. http://dx.doi.org/10.3390/ijerph17114040. PMid:32517097.
16. Lopes GDRS, Matos JDM, Queiroz DA, Tribst JPM, Ramos NC, Rocha MG, et al. Influence of abutment design on biomechanical behavior to support a screw-retained 3-unit fixed partial denture. Materials (Basel). 2022;15(18):6235. http://dx.doi.org/10.3390/ma15186235. PMid:36143553.
17. Silveira MPM, Campaner LM, Bottino MA, Nishioka RS, Borges ALS, Tribst JPM. Influence of the dental implant number and load direction on stress distribution in a 3-unit implant-supported fixed dental prosthesis. Dent Med Probl. 2021;58(1):69-74. http://dx.doi.org/10.17219/dmp/130847. PMid:33687804.
18. O'Mahony AM, Williams JL, Katz JO, Spencer P. Anisotropic elastic properties of cancellous bone from a human edentulous mandible. Clin Oral Implants Res. 2000;11(5):415-21. http://dx.doi.org/10.1034/j.1600-0501.2000.011005415.x. PMid:11168233.
19. Miyashiro M, Suedam V, Moretti Neto RT, Ferreira PM, Rubo JH. Validation of an experimental polyurethane model for biomechanical studies on implant supported prosthesis--tension tests. J Appl Oral Sci. 2011;19(3):244-8. http://dx.doi.org/10.1590/S1678-77572011000300012. PMid:21625741.

20. Bölükbaşı N, Yeniyol S. Number and localization of the implants for the fixed prosthetic reconstructions: on the strain in the anterior maxillary region. Med Eng Phys. 2015;37(4):431-45. http://dx.doi.org/10.1016/j.medengphy.2015.02.004. PMid:25765190.
21. Hekimoglu C, Anil N, Cehreli MC. Analysis of strain around endosseous dental implants opposing natural teeth or implants. J Prosthet Dent. 2004;92(5):441-6. http://dx.doi.org/10.1016/j.prosdent.2004.07.023. PMid:15523333.
22. Almeida EO, Rocha EP, Freitas AC Jr, Anchieta RB, Poveda R, Gupta N, et al. Tilted and short implants supporting fixed prosthesis in an atrophic maxilla: a 3D-FEA biomechanical evaluation. Clin Implant Dent Relat Res. 2015;17(Suppl 1):e332-42. http://dx.doi.org/10.1111/cid.12129. PMid:23910435.
23. Liu X, Pang F, Li Y, Jia H, Cui X, Yue Y, et al. Effects of different positions and angles of implants in maxillary edentulous jaw on surrounding bone stress under dynamic loading: a three-dimensional finite element analysis. Comput Math Methods Med. 2019;2019:8074096. http://dx.doi.org/10.1155/2019/8074096. PMid:31933678.
24. Tribst JPM, Dal Piva AMO, Bottino MA, Nishioka RS, Borges ALS, Özcan M. Digital image correlation and finite element analysis of bone strain generated by implant-retained cantilever fixed prosthesis. Eur J Prosthodont Restor Dent. 2020;28(1):10-7. http://dx.doi.org/10.1922/EJPRD_1941Tribst08. PMid:31638348.
25. Wu AY, Hsu JT, Fuh LJ, Huang HL. Biomechanical effect of implant design on four implants supporting mandibular full-arch fixed dentures: in vitro test and finite element analysis. J Formos Med Assoc. 2020;119(10):1514-23. http://dx.doi.org/10.1016/j.jfma.2019.12.001. PMid:31883628.
26. Tribst JP, Rodrigues VA, Dal Piva AO, Borges AL, Nishioka RS. The importance of correct implants positioning and masticatory load direction on a fixed prosthesis. J Clin Exp Dent. 2018;10(1):e81-7. http://dx.doi.org/10.4317/jced.54489. PMid:29670721.
27. Tribst JPM, Rodrigues VA, Borges ALS, Lima DR, Nishioka RS. Validation of a Simplified Implant-Retained Cantilever Fixed Prosthesis. Implant Dent. 2018;27(1):49-55. http://dx.doi.org/10.1097/ID.0000000000000699. PMid:29341975.
28. Datte CE, Datte FB, Borges ALS, Campos JF, Lopes GDRS, Tribst JPM, et al. The influence of restorative material, bone height and implant system on the stress distribution of implant-supported posterior crowns. Int J Dev Res. 2021;11:44925-31.
29. Ahmed MA, Hamdy AM, Fattah GA, Effadl AK. Prosthetic design and restorative material effect on the biomechanical behavior of dental implants: strain gauge analysis. Braz Dent Sci. 2022;25(3):e3380. http://dx.doi.org/10.4322/bds.2022.e3380.
30. Ozan O, Ramoglu S. Effect of implant height differences on different attachment types and peri-implant bone in mandibular two-implant overdentures: 3D finite element study. J Oral Implantol. 2015;41(3):e50-9.; http://dx.doi.org/10.1563/AAID-JOI-D-13-00239. PMid:24471769.
31. Paes T Jr, Tribst JP, Dal Piva AM, De Figueiredo VM, Borges AL, Inagati CM. Influence of fibromucosa height and loading on the stress distribution of a total prosthesis: a finite element analysis. Braz Dent Sci. 2021;24(2):1-7.
32. Matos JDM, Lopes GDRS, Nakano LJN, Ramos NC, Vasconcelos JEL, Bottino MA, et al. Biomechanical evaluation of 3-unit fixed partial dentures on monotype and two-piece zirconia dental implants. Comput Methods Biomech Biomed Engin. 2022;25(3):239-46. http://dx.doi.org/10.1080/10255842.2021.1946798. PMid:34559574.
33. Matos JD, Gomes LS, de Carvalho Ramos N, Queiroz DA, Tribst JP, Campos TM, et al. Influence of CAD/CAM Abutment Heights on the Biomechanical Behavior of Zirconia Single Crowns. Metals (Basel). 2022;12(12):2025. http://dx.doi.org/10.3390/met12122025.

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