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Finite Element Analysis (FEA) of Palatal Coverage on Implant Retained Maxillary Overdentures

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Received: 12 August 2020; Accepted: 18 September 2020; Published: 23 September 2020

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Abstract: Purpose: The aim of this study was to determine stress levels on supporting structures of implant-retained overdentures as a function of varying degrees of palatal coverage using finite element analysis modeling at different loading angles. Materials and Methods: ABAQUS®-software was used to perform finite element analysis on eight overdenture models with three and four implants and with and without palatal coverage designs. Loads were applied perpendicular and 45° to the implants. Von Mises stress was measured to determine bone stress. A one-way ANOVA determined which model caused the most stress to the maxillary bone. Results: Palatal coverage increased stress to anterior implant in three implant (p = 0.08) models but decreased stress to all implants in four implant models (p = 0.43). Distal implants received more stress than anterior implants for all models. There was no significant difference between a full palate and no palate coverage overdenture prosthesis when a bar was added under axial loading (p = 0.954). Under non-axial loading, a decrease in stress was noted with the bar in all areas except the anterior implant site. Conclusions: Palatal coverage may not be necessary when applying a pure axial load. The addition of a bar decreased stress at loading.

Keywords: maxillary overdenture; overdenture design; implant retained removable prosthesis; denture palatal design; implant loading; implant stress distribution; bar splinted implants; implant superstructure; finite element analysis

1. Introduction

Maxillary implant-retained overdentures are considered a favorable treatment option for patients with insufficient bone volume, retention, and stability complaints [1–7]. However, a consensus is lacking regarding the adequate number of implants necessary to support a maxillary overdenture or the different anchorage systems used [8–13]. In addition, the impact of palatal coverage design, as well as the effect of implant splinting on the biomechanical behavior of implant-retained maxillary overdentures, is not clear in the literature [14–17].

There is conflicting information regarding the influence of palatal coverage on maxillary implant retained overdentures. Designs with no palate are selected for patients with large palatal tori or an exacerbated gag reflex, and also to improve temperature, motor, and sensory function. This implant overdenture design is associated with high patient satisfaction and implant success [18–24]. However, prosthetic and/or implant complications may occur as a result of functional loading and prosthetic component fatigue as reported in the literature [25–27]. Some of the reported complications are: (1) screw loosening or screw fracture; (2) attachment fracture; (3) implant failure and; (4) denture or teeth fracture, etc. Rodriguez et al. [28] and Cehreli et al. [29] agreed in their investigations that a palateless designed implant overdenture could be a considerable risk factor for implant failure due to the inferior rigidity and strength of the prosthesis. Sadowsky et al. [9,10] and Ochiai et al. [15] demonstrated that implant overdentures with palatal coverage had reduced wear of attachment components and less overdenture base fractures when compared with palateless overdentures.

The effect of splinting versus no splinting of implant attachments is also controversial. Most of the literature seems to favor bar attachment splinting because of better implant load distribution [17,30–34]. However, splinting superstructures have many disadvantages, such as need for vertical space, restrictions on implant distribution and alignment, complex clinical and laboratory procedures, and difficulty of home cleaning for the patient. On the contrary, implant overdentures with unsplinted attachments have the highest patient satisfaction with less maintenance needs and a reduced treatment cost for the patients [35]. Additionally, the literature reports more prosthetic, soft tissue, and implant complications when implants are not splinted. The most commonly reported complications are: (1) denture fractures; (2) attachment fractures; (3) implant failures; and (4) soft tissue ulcers, etc. [9,10,15,25–27,36].

Most of the current literature agrees that implant geometry and bone density are key factors of implant osseointegration [36,37] Load transfer mechanisms and possible failure of osseointegrated implants are affected by implant design, diameter, and length as well as properties of the site of placement and prosthetic component designs. Factors such as material biocompatibility, implant design and surface, surgical technique, host bone quality, and the loading conditions have all been shown to influence the implant osseointegration [38,39].

Thread design, surface roughness, length, and diameter of the implant fixture have all been shown to influence the surface area available for bone contact. Selecting implant characteristics that maximize the available surface area for bone contact should be considered for successful implant rehabilitations of poor-quality bone sites [40,41]. Thus, threaded implants are preferential to cylindrical implants as a result of their ability to minimize undesirable force components when prosthetically loaded. Prosthetic engineering of the final implant appliance also greatly influences the distribution of masticatory force during function. Particular attention should be given to evenly distributing the masticatory load of the prosthesis, and protecting implant occlusion through assuring that the proper number of implants are placed for the span of missing dentition. When selecting potential areas for implant rehabilitation, consideration should be given to maximize the amount of available bone to allow for the placement of 10 mm or longer implants with 4 mm or wider diameter fixtures [42,43].

Regarding the ideal number of implants to support maxillary overdentures, Duyck et al. [44] found in his study that when comparing a prosthesis supported by three or four implants, the difference in axial force was not statistically significant. The bending moments, however, were significantly higher with three supporting implants in comparison with four supporting implants.

Frost et al. [45] in his research states that bone function typically ranges between approximately 50–1500 (1–2 MPa) micro-strain. If peak load of bone results in strains of 1500–3000, a mild overload occurs, resulting in mechanical fatigue damage, but remodeling normally repairs the damage and thus prevents the damage from accumulating. Moreover, repeated micro-strain greater than 3000 (60 MPa) increases micro-damage. Normal bone fractures suddenly occur at forces of 25,000 micro-strain (120 MPa). The view that non-axial load is more detrimental to oral implants than axial load is further supported by findings in studies using 3D FEM analysis by Papavasiliou et al. [39] and Kitamura et al. [46], where non-axial loads resulted in higher stress levels in the peri-implant bone area when compared with axial loads.

Therefore, the purpose of this study was to determine the effect of palatal coverage and implant splinting superstructures on their supporting structures by measuring the stress and strain forces in implant supported maxillary overdentures along the bone–implant interface, implant–prosthesis interface, and within the prosthesis by applying axial and non-axial loads using finite element modeling for stress/strain analysis.

2. Materials and Methods

Eight different three-dimensional finite element maxilla models were created and analyzed. The finite element models were designed as follows:

(A) Four-implant retained maxillary overdenture designed without and with full palatal coverage excluding a connecting bar.
(B) Three-implant retained maxillary overdenture designed without and with full palatal coverage excluding a connecting bar.
(C) Three-implant retained maxillary overdenture without and with full palatal coverage designed to connect the implant fixtures with a titanium bar.
(D) Four-implant retained maxillary overdenture without and with full palatal coverage designed to connect the implant fixtures with a titanium bar.

The abutment geometry and dimensions were made to replicate a two-millimeter (Zest Anchors) Locator® abutment for the three- and four-implant retained overdenture models excluding the connecting bar.

The maxillary FEA prototype was created using computer-aided design (CAD) from a model supplied by Dentsply Sirona Inc. (Charlotte, North Carolina, United States). Due to the symmetrical nature of the maxilla, the finite element models were created using one half of the prototype to reduce computation time. The three-implant symmetric model contained one whole implant and another half implant (Figure 1). The symmetrical maxillary model with four-implants was fabricated using two implants as shown in Figure 2. The implant position and location are described in Figure 3. For both symmetrical models the implant diameter selected was 4 mm, and the implant length was 11 mm. The length of the implant above the surface of the cortical bone was 3.5 mm for all models. The thickness of the cortical bone was 2 mm in all cases.

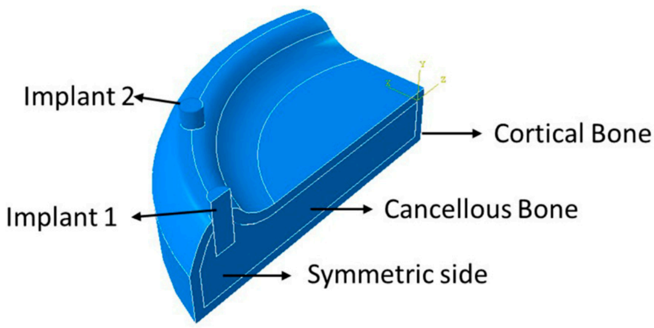

Figure 1. One half of the maxilla (three-implants model).

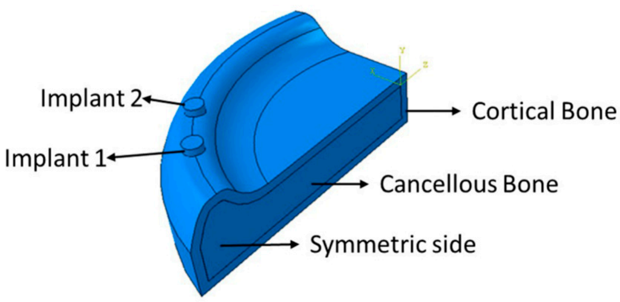

Figure 2. One half of the maxilla (four-implants model).

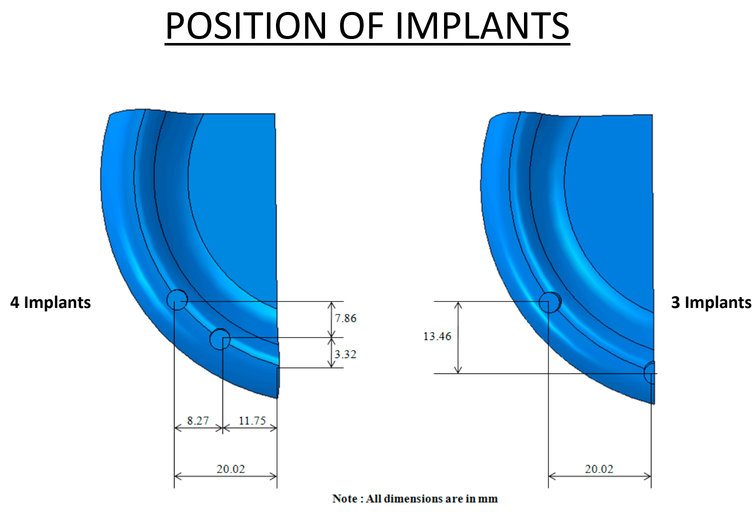

Figure 3. Position of implants for the four-implant and three-implant FEA models.

The FEA part attributes for the three- and four-implant models are described in Figures 4 and 5, respectively. The maxilla prototype consisted of two layers: a cortical layer and a cancellous layer.

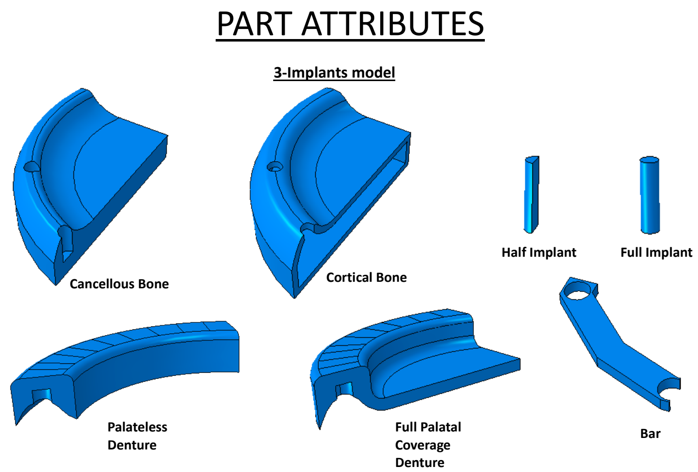

Figure 4. Part attributes for the FEA three-implant models.

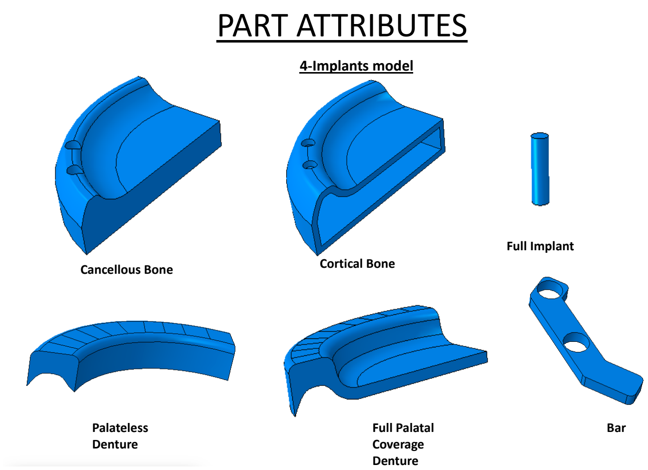

Figure 5. Part attributes for the FEA four-implant models.

The jaw bone properties in the model were set with a Young's Modulus of 13.5 GPa for the cortical bone and 1.35 GPa for the cancellous bone. Poisson's ratio was set at 0.3 for both cortical and cancellous bones. The titanium bar connecting the implants had a Young's modulus of 107 GPa and a Poisson's ratio of 0.3. The polymethyl methacrylate (PMMA) was set with a Young's modulus of 3.4 GPa and a Poisson's ratio of 0.35. The interface between the cortical and cancellous bone layers and between the implant and each of the bone layers was assumed to be well bonded, which corresponds to good osseointegration. The implant–prosthesis interface was also well bonded. The lower surface of the model and the medial and distal planes of the bone were completely constrained. The boundary conditions were set with the bottom of the maxilla fixed. All the degrees of freedom (dof) were constrained on the bottom. The symmetrical boundary condition was imposed on the symmetry axis of the model. The interaction for the surfaces of the inner and outer bone were tied. The surfaces of the implants were also tied to the respective side and bottom surfaces of the inner and outer bone.

Each model was composed of a mesh that had 41,000 elements and 60,000 nodes made of tetrahedron 3D quadratic solid elements, with an improved modified formulation (C3D10M) used to generate all the parts. A linearly varying load maximum at the position of the second implant (distal implant) and minimum at the model center (mesial implant) was applied on the denture such that the loads on the four-implants model were 187.5 N and 137.5 N respectively. For the three-implants model, the loads were also 187.5 N at the distal implant and 137.5 N at the center of the model. The connecting bar design loaded the bar directly, while the Locator® attachment design loaded the implant through the PMMA overdenture. The applied varying forces were simulated, with bucco-lingual loading angles ranging from 0 to 45 degrees. All computations were performed using ABAQUS®—the Finite Element software—for the analysis of finite element program.

One-way analysis of variance (ANOVA) was performed to compare each model combination. The ANOVA test determined which combination caused the most stress to the maxillary bone, bone–implant interface, implant–prosthesis interface, and within the prosthesis.

3. Results

An analysis of variance was conducted to determine stress levels on the supporting structures of implant-supported overdentures using finite element analysis modeling as a function of different variables. These variables included: (I) full-palatal-coverage vs. palateless denture models; (II) supporting bar vs. no bar denture models; (III) loading angles at 90 degrees vs. 45 degrees; and (IV) three- vs. four-implant models.

The statistical analysis for the effects of loading on cancellous bone by denture design using the ANOVA test for difference in means was significant ($p = 0.047$). Pairwise comparisons showed that the stress level on the three-implant-full-palate-coverage combination was significantly higher than on the three-implant-palateless model ($p = 0.016$), higher than the four-implant-palateless model ($p = 0.038$), and higher than the four-implant-full-palate-coverage ($p = 0.016$). No other pairs were significantly different.

An independent *t*-test for difference in means to compare both denture designs and three- vs. four-implant conditions was performed. For the palateless denture design variable, the means [medians] were 2.6 (0.50) [2.6] vs. 3.9 (2.6) [3.0] for the full-palate-coverage design with ($p = 0.203$).

For the model with three implants vs. four implants, the means [medians] were 3.9 (2.6) [2.9] for the three-implant model and 2.6 (0.52) [2.7] for the four-implant model with ($p = 0.211$).

To compare the effect of loading on cortical bone in palateless vs. full-coverage denture designs with three-implants and four implants conditions, a one-way ANOVA between models was conducted. Results showed that there was a significant loading effect on the cortical bone for the three-implant full coverage model ($p < 0.0001$). Pairwise comparisons showed that the three-implant-full-coverage model was significantly higher than the three-implant-palateless ($p < 0.0001$) and significantly higher than four-implant-palateless ($p < 0.0001$); four-implant-full-coverage was significantly higher than three-implant-palateless ($p < 0.001$), and higher than four-implant-palateless ($p < 0.0001$). No other pairs were significantly different.

An independent *t*-test for difference in means to compare both denture designs and three-implants vs. four-implants variables was performed. For the denture designs the means [medians] were 3.2 (4.1) [2.8] for the palateless design vs. 12.5 (2.5) [13.8] for the full-palate-coverage, with the *t*-test result ($p < 0.0001$).

For the model with three implants vs. the one with four implants the means [medians] were 7.9 (5.4) [8.3] for the three-implant model, (Figure 6) and 7.8 (6.3) [6.5] for the four-implant model (Figure 7). The *t*-test result for difference in means was ($p = 0.964$).

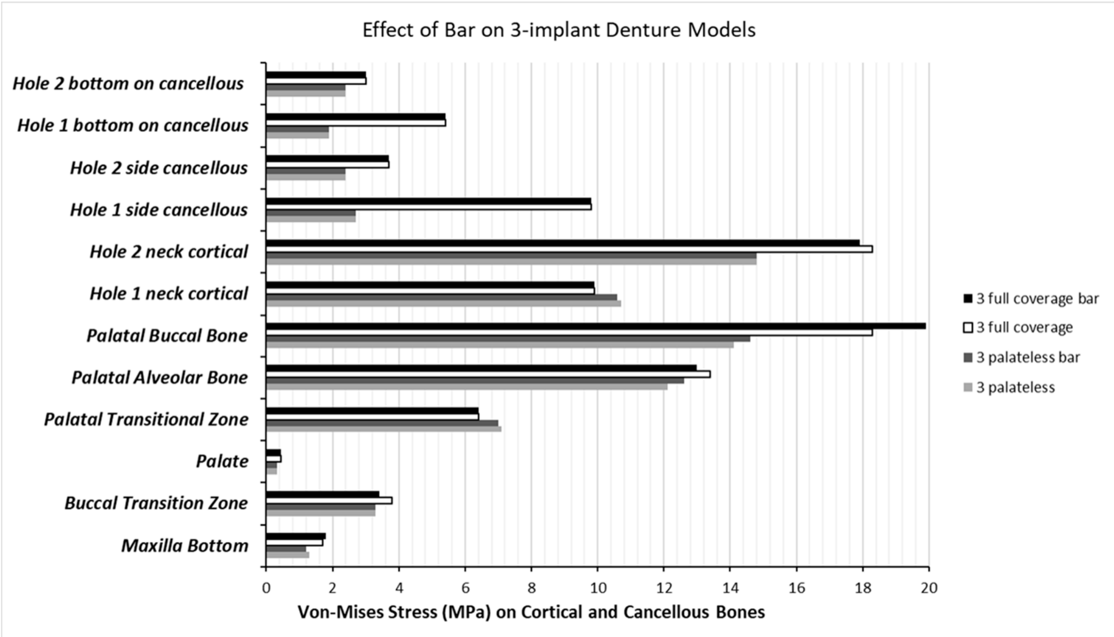

Figure 6. Effect of Bar on three-implant overdenture models with axial loading.

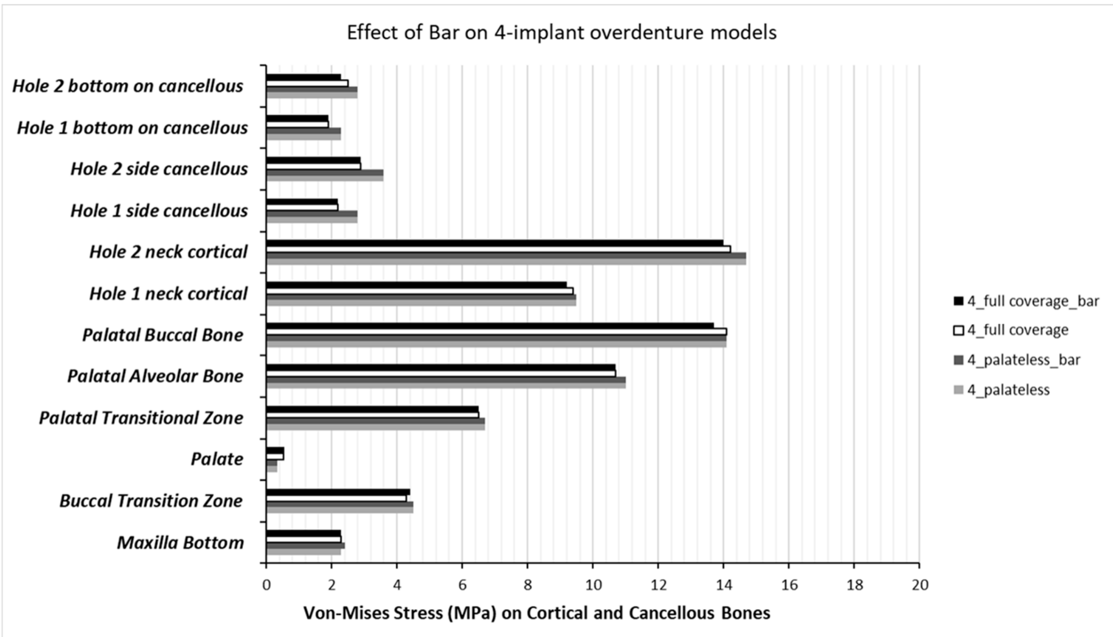

Figure 7. Effect of bar on four-implant overdenture models with axial loading.

The statistical analysis for the effects of the supporting bar on cortical and cancellous bone for the three- vs. four-implant models using the ANOVA test for difference in means was not significant.

The results for the three-way interaction were not significant ($p = 0.988$). Likewise, no two-way interactions were found significant (all $p > 0.3$). The results for the palateless vs. full-coverage denture model showed ($p = 0.507$). For the three-implant vs. four-implant model ($p = 0.398$). For the bar vs. no-bar model ($p = 0.993$). Hence, no individual factors were significantly associated with the outcome.

The global analysis of variance conducted to determine stress levels on the implants by location and the bar superstructure was significant ($p < 0.001$). Pairwise comparisons showed that the stress levels on implant at location 1 was significantly higher than the bar superstructure ($p = 0.014$), stress on implant at location 2 was significantly higher than at the bar ($p = 0.0001$), and on implant at location 2 was significantly higher than on the Implant at location 1 ($p = 0.014$).

The mean (SD) [median] for Implant at location 1 was: 32.3 (3.2) [31.5]; for Implant at location 2 was: 42.7 (6.8) [39.2] and for the bar superstructure was: 19.6 (13.8) [22.9].

For the effect of 45 degrees loading on the bone for the three-implant (Figure 8) vs. the four-implant models (Figure 9), the analysis of variance conducted showed that there was not significant difference when the bar vs. no-bar models were compared ($p = 0.638$). The mean (SD) median for the no-bar model: 9.2 (11.4) [2.6] vs. the bar model: 7.8 (9.7) [2.4]. For the no-bar vs. bar model with three implants the mean (SD) [median] difference was 1.7 (3.3) [0.2] with ($p = 0.059$). For the no-bar vs. bar model with four implants the mean (SD) [median] difference was 1.2 (1.6) [0.35] with ($p = 0.014$). For the no-bar–bar models with three and four implants combined the mean (SD) [median] difference was 1.4 (2.6) [0.2] with ($p = 0.002$).

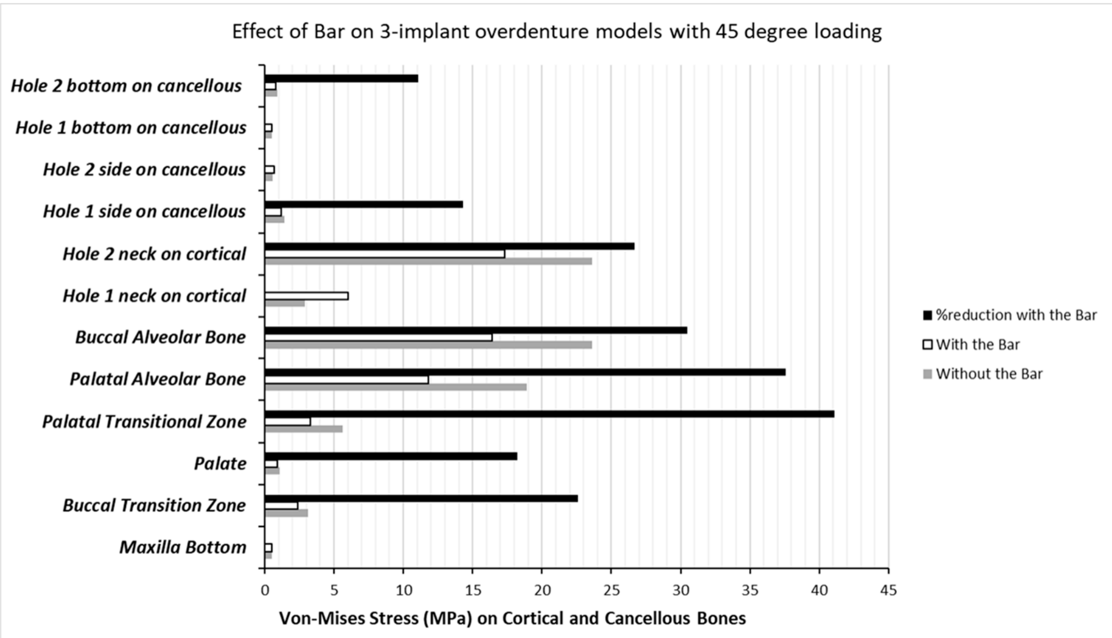

Figure 8. Effect of bar on three-implant overdenture models with 45-degree loading.

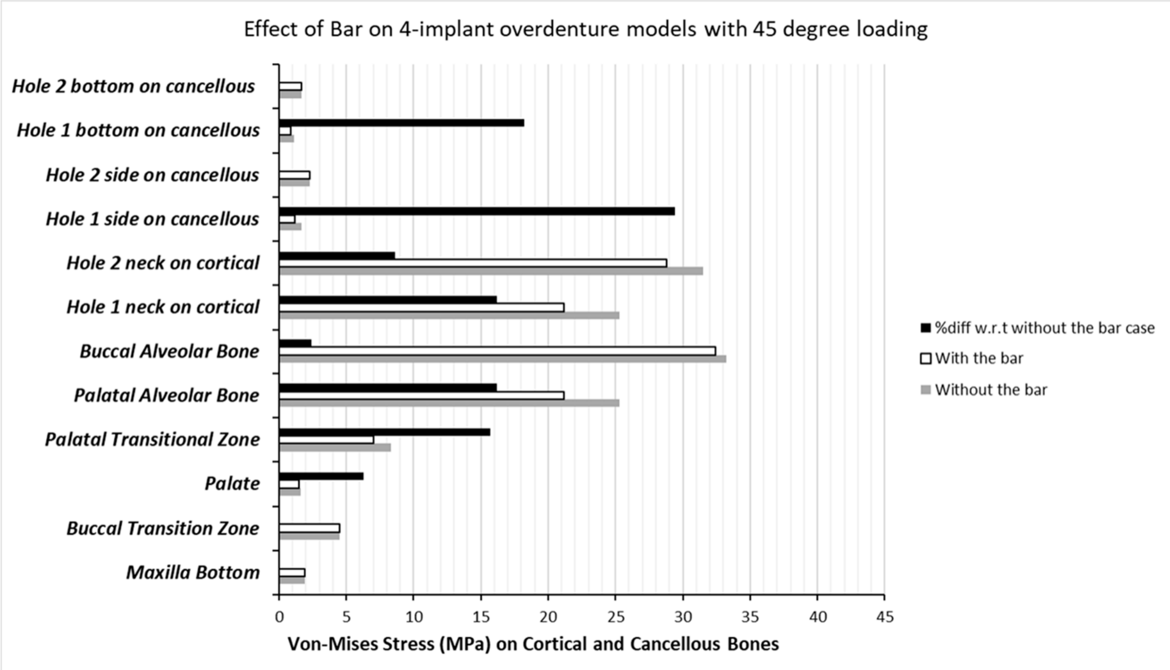

Figure 9. Effect of bar on four-implant overdenture models with 45-degree loading.

4. Discussion

Since the stress and strain distribution at the bone level is very difficult to evaluate in a clinical setting, FEA is used in dentistry to evaluate and quantify these stresses conveyed from the prosthesis to the implants and to the supporting tissues [44,45]. There are a few studies in the literature that have attempted to evaluate the stress and strain distribution at the abutment level using in vivo strain gauge analysis [46–49]. However, these methods still do not provide a complete understanding of the overdenture stress distribution, nor do they provide sufficient basis to draw conclusions about the need for implant splinting [17,32,35]. Ideally, the loads in implant supported prostheses should be evenly distributed across all components and supporting structures. Therefore, excessive force concentration in a particular area of the superstructure or prosthesis should be avoided. Bone resorption may occur when excessive stress loads are applied to the supporting bone, and if left unattended implant failure could follow [1,7,19]. Also, when extra stresses are applied to the implant fixtures and or the superstructure components, prosthetic complications—such as screw loosening or screw fracture or fracture of the abutments, etc.—could occur [36,42,48,50–52]. The photoelastic method [15,40] has also been used in vitro to analyze how stresses are conducted and absorbed from the prosthesis to the implants and supporting tissues.

When comparing the quality of the bone in the maxilla with the mandibular bone, cancellous bone is not as dense in the maxilla and cortical bone is thinner than in the mandible [53]. Consequently, the design of maxillary implant overdentures should include palatal coverage to help with the prosthesis support and to alleviate stress concentration on the supporting implants as suggested in the literature [54]. Hence, palatal coverage could help maintaining the bone around the supporting implants.

Ochiai et al. [15] and Cehreli et al. [29] used photoelastic analysis to study the role of palatal coverage in maxillary overdentures. They both reported that covering the palate seemed beneficial to the load concentration and distribution over the supporting implants and bone. The findings from this study suggest that more stress was seen in the cortical bone compared to the cancellous bone in all models as expected. However, this study found that palatal coverage may not be necessary when applying axial forces in contrast with some of the above studies (Figure 10).

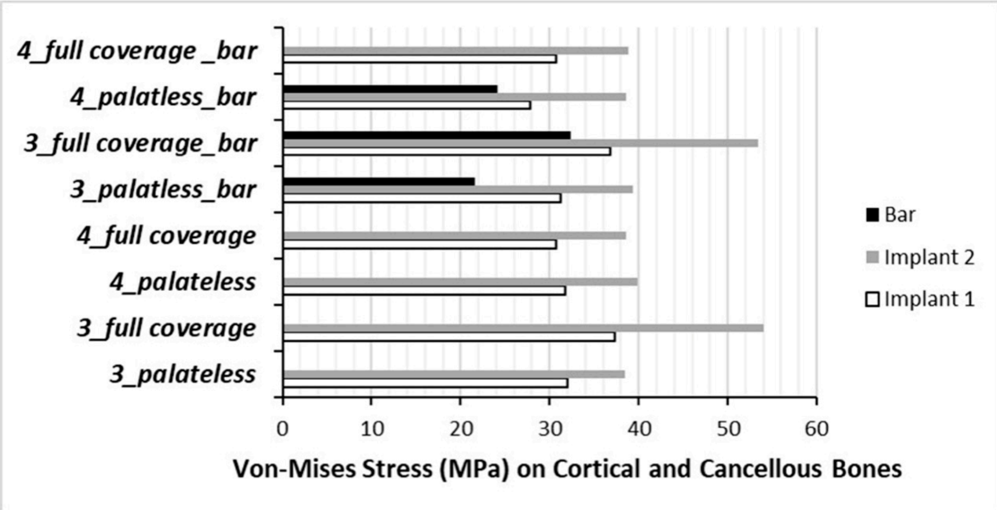

Figure 10. Von Mises stress (MPA) in cortical and cancellous bone for palateless three- and four-implant models with and without connecting bar.

Occlusal forces in patients with implant overdentures could range between 48–258 N with an average of 128 N [40,41]. Additional studies in implant overdentures analyzing oblique and a horizontal load in combination with axial loads have found axial loads to range from 100–300 N and also established that the lateral forces could be a quarter (25 N) that of the axial load [43,44]. In this study, a linearly varying load of 187.5 N at the position of the distal implant and 137.5 N at the model center was applied on the three and four-implant models [55]. The applied varying forces were simulated, with bucco-lingual loading angles ranging from 0 to 45 degrees. The three-dimensional finite element analysis in this study indicated that the higher stresses after implant loading were dependent on the direction of the force and the presence of a splinting superstructure. The finite element models showed that the cortical bone absorbed most of the loading forces and, depending on the palatal extension of the prosthesis, varied in location from the alveolar crest to the palate. Furthermore, the finite element models exposed to 45-degree forces exhibited stress concentration greater than those exposed to axial forces. In this study, the implant splinting with the connecting bar showed a decrease in stress except at the anterior implant site (Figure 11).

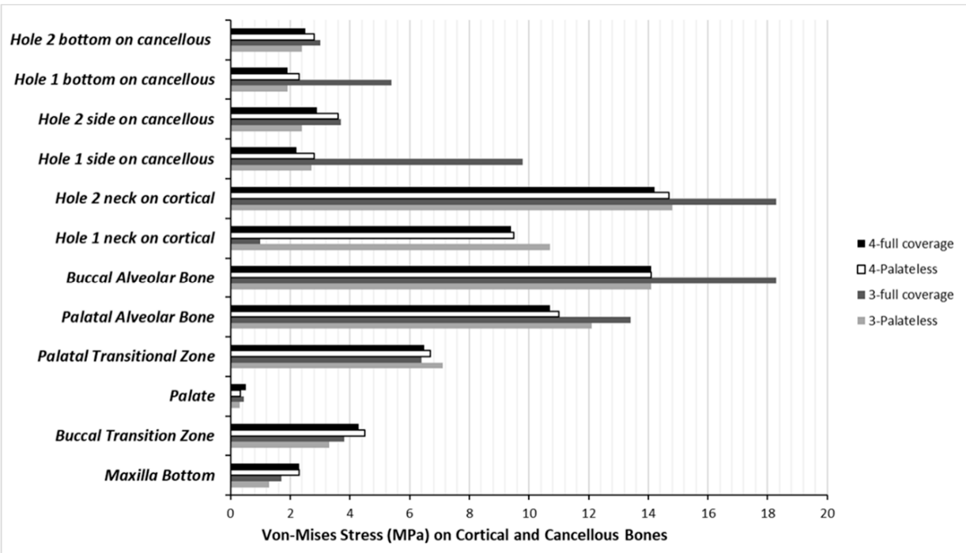

Figure 11. Results for axial loadings on three- and four-implant models with and without palatal coverage.

One limitation of this study is that the non-axial loading could have been applied linearly and not directly to the implants. Likewise, non-axial loading could have been applied to the locator models. Additionally, since this FEA study was conducted under the premise that implant fixtures and connecting bars were well bonded as one structure, the stresses applied to the superstructure components, like the internal joints and the connecting screws between the abutments and the implant fixtures, were not analyzed. There may be some other possible limitations resulting from the loads applied only at the surface of the implants and not at a more distal location from the implants such as what commonly occurs during food chewing and normal function. The effect of loads applied on the distal cantilever could have shown a different stress distribution at the implant/bone interface due to rotational forces posterior to the fulcrum line. Furthermore, loading the bar overdenture on one side only would be a more similar action to the natural eating process instead of the bilateral loading used in this study.

Another important consideration in this study is that all the implants inserted in the FEA models are parallel to each other and present no tilt or angulation. This contrasts with what often happens with these types of rehabilitations where implants have different degrees of angulations and tilts.

Also, there are inherent limitations of the FEA modeling like the bone implant contact (BIC) set at 100% due to the inability to modify the modeling. Moreover, FEA studies cannot take into consideration the so called "Realeff Effect (resilient and like effect)" discussed by Rudolph Hanau [56] as well as the flexibility of the attachment housings.

Therefore, the findings presented in this report are restricted to these tested conditions and should be considered transferable to clinical situations carefully.

Since the results of this study are empirical, additional laboratory and clinical investigation are necessary to clarify the effect and role of palatal design, number, angulation and location of implants, superstructure design, and non-axial loading effect on maxillary implant retained overdentures. Higher quality of evidence is needed to support treatment modalities for the edentulous maxilla.

5. Conclusions

Within the limitations of this study, the following conclusions can be drawn: (a) under axial loading palatal coverage increased stress to anterior implants but decreased stress to all implants in all implant models; (b) distal implants received more stress than anterior implants for all models; (c) there was no significant difference between a full palate and no palatal coverage overdenture prosthesis when a bar was added under axial loading; and (d) under non-axial loading, a decrease in stress was noted with the bar in all areas except the anterior implant site.

Therefore, palatal coverage may not be necessary when applying a pure axial load. The addition of a bar decreased stress at loading.

Author Contributions: M.A.F., methodology, writing, original draft preparation, editing; N.S., software, methodology, validation; M.N., conceptualization, methodology, investigation, A.N., conceptualization, methodology, investigation; J.C., conceptualization, methodology, investigation; A.C., conceptualization, formal analysis, review and editing; E.O., conceptualization, methodology, data curation; D.N. statistical analysis, visualization, data curation, validation; J.E.-U., project administration, conceptualization, methodology; writing, review, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research project was partially funded by NIH-NIDCR R01 DE025001 and the University of Florida Graduate Prosthodontics Program. The APC was funded by NIH-NIDCR R01 DE025001.

Conflicts of Interest: The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work.

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