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QCT/FEA ANALYSES OF PALATELESS SPLINTED AND UNSPLINTED MAXILLARY ALL-ON-4 SYSTEMS

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Abstract. The goal of the presented study was to determine the viability of using splinted and unsplinted maxillary implant-supported overdentures. The main physical quantity used to evaluate their differences was compressive stress in bone and equivalent (von Mises) stress in the implant and overdenture components. We took a 3D X-ray scan of the maxilla and imported the data into a QCT/FEA (Quantitative Computed Tomography-based Finite Element Analysis) software. The loading was done in three load cases. We designed both models of the overdentures in CAD, included the polyetheretherketone (PEEK) overdenture and analyzed the whole model of the reconstructed maxilla with implants. The results show worse (more concentrated) compressive stress distributions for the unsplinted locator variant. The splinted, bar-retained variant shows lower values of stress in all load cases. These findings and their potential for real-time selection of the optimal variant are then further discussed.

Keywords: QCT/FEA, implant-supported overdenture, splinted, unsplinted, all-on-4.

1. Introduction

Alongside conventional methods including removable dentures, there has been a growing share of implant-based solutions since the formal acceptance of dental implants for tooth loss rehabilitation in 1978. These implants can either serve in fixed restorations or to stabilize complete removable dentures, as shown by an implant-supported overdenture (IOD) [1]. It is vital for this treatment option to have thorough assessment, with its indications initially outlined in the 1990s [2]. This option proves to be advantageous for patients with limited bone quality [3]. Edentulousness has been following a downward trend for over 10 years, but there is still a global concern due to demographic shifts towards an aging population.

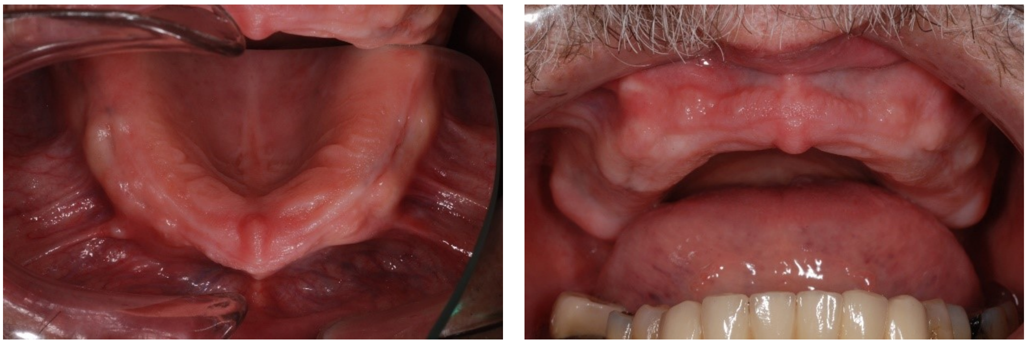
Connecting the overdenture to the supporting dental implants can be done by various types of attachments including both unsplinted and splinted designs (bars and clips) [5–7]. To date, consensus has not been reached regarding the superior option [8]. Bar-supported (splinted) restorations offer better retention and show improved stability for dentures [9]. Bars can withstand lateral motion and rotation during function, facilitating a more even distribution of force across fixtures [7, 10]. However, their application may elevate the likelihood of mucosal issues and hyperplasia due to suboptimal oral hygiene [11].

While the unsplinted design may have its advantages in terms of treatment simplicity, duration, hygiene, and cost [12], evidence regarding the impact of splinting versus non-splinting on the load distribution of upper jaw overdentures remains relatively limited and sometimes contradictory [13]. In a literature review with a comparable follow-up duration, survival rates are 88.9 % for unsplinted implants in the upper jaw, whereas splinted attachments showed an implant survival rate exceeding 97 % [14].

The absence of standardized techniques, implant quantities, differing measurements of marginal bone and loading conditions in studies may contribute to the subjective preference for unsplinted or splinted attachments for maxillary overdentures [2]. Therefore, a more precise assessment of the biomechanical distinctions between these two alternatives is needed.

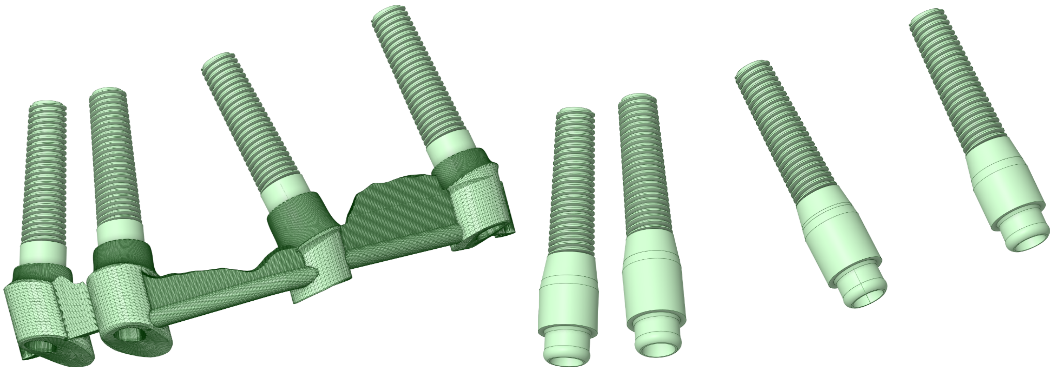
To simplify complex problems into a system of algebraic equations, we can use the finite element method (FEM) that provides insights into the behavior of the analyzed system. FEM proves beneficial in solving intricate geometries, achieving numerical solutions for highly complicated stress problems via finite element analysis (FEA) [15]. This technique has been effectively applied in examining stress and strain in implant dentistry [16]. With the increasing availability of 3D imaging techniques, such as quantitative computed tomography (QCT), accurate reconstruction of the upper jaw bone is now possible, enabling QCT/FEA for analyses of stress distributions at the bone-implant interface.

This study aims to compare stress distribution in the maxillary bone, dental implants, and prosthetic components of upper jaw overdentures in both splinted and unsplinted designs, using QCT/FEA. The null hypothesis is that the splinted design will demonstrate



(A). Occlusal view. (B). Front view.

FIGURE 1. The view of the patient's residual alveolar ridge [4].



(A). The splinted, bar-supported variant. (B). The unsplinted, locator-supported variant.

FIGURE 2. Analyzed variants of the All-on-4 system. Assemblies designed to fit the individual patient. Geometries are identical, short of the splints [4].

superior biomechanical performance compared to the unsplinted design. To validate or refute this hypothesis, this study focuses on these two types of IODs.

Usually, other authors' analyses use a two-phase (cortical and cancellous) linearly elastic, homogeneous model. However, these assumptions do not adequately mirror the intricate nature of bone tissue [17]. The use of 3D imaging and QCT/FEA can offer more realistic simulations of bone-implant interface behavior [18]. The present study aims to provide more precise results of biomechanical performance of implant-supported upper jaw overdentures by using a more detailed model.

2. Materials and Methods

The anonymous patient who provided his 3D X-ray data for this study was a 76-year-old male with sufficient dexterity. We had obtained the patient's written consent prior to conducting the study.

All extraoral and intraoral criteria for an implant-supported overdenture in the maxilla were met [3]. Buccal inclination of the residual ridge (Figure 1) was present. The patient was predetermined for an anterior maxillary concept based on insufficient bone quality in distal regions, but sufficient quality in the frontal region.

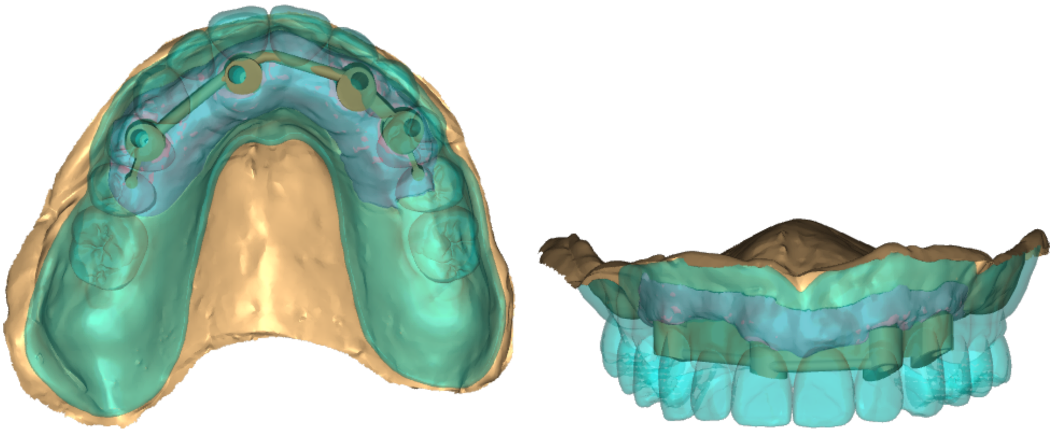
The implants used were manufactured by Straumann (SLA RN SP Roxolid®) and placed in sites with good bone quality as follows: the upper-right first premolar (4.8 mm in diameter, 14 mm in length), upper-right first incisor (3.3 mm in diameter, 12 mm in length), upper-left second incisor (4.1 mm in diameter, 12 mm in length), and upper-left first premolar (4.1 mm in diameter, 12 mm in length). The 3D X-ray scans were acquired with Planmeca ProMax® 3D Classic.

The approach used to evaluate the patient-specific 3D X-ray scans acquired with Planmeca ProMax® 3D Classic using Romexis® 3D imaging was done using QCT/FEA. The 3D X-ray, along with the implant positions, shapes, and locations, were modeled based on data provided by the patient. For a visual representation of the analyzed implant variants, see Figure 2.

The QCT/FEA model includes both the cancellous and cortical bone. The design of the complete denture and abutments was done using Exocad (Exocad Gmbh Darmstadt, Germany) in the dental laboratory. The denture was made without a palate. For visual reference, the denture with the splinted variant is shown in Figure 3. The denture was made out of polyetheretherketone (PEEK).

2.1. Methodology

The analyses were performed using a specialized QCT/FEA software for nonlinear analysis of bone-implant interaction Mechanical Finder v. 12.0 (RCCM,



(A). Occlusal view. (B). Front view.

FIGURE 3. The view of the entire scene. The splinted variant is displayed [4].

Tokyo, Japan). The software uses sliced image data, like CT or X-ray scans. The QCT/FEA method allows for analyses using complete material inhomogeneity, where each voxel, and then finite element, possesses individual material properties specific to the individual patient's bone quality. Conventional modeling methods typically represent bone with a two-phase model (cancellous, cortical). For this study, the patient's maxilla was reconstructed from an X-ray scan, and two different implant geometries were examined.

2.2. Boundary Conditions

The loading was performed in three load cases for both analyzed variants. The first one was a 150 N force with a 35° slant in the buccolingual direction applied in the frontal region (both incisors). The second was a 600 N force with a 5° inclination applied in the distal region on both molars. The third was a 600 N force with the vertical component only, applied in the distal region on the first premolar tooth. To unify the visual appearance of the results, the color bar's upper and lower limits were normalized.

3. Results

3.1. Stress Distributions in Implants

The stress distribution in bone is similar for both alternatives in the frontal region. Moreover, the equivalent stress levels in implants show almost no difference between the two variants. Notably, even in the unsplinted alternative, the load was effectively transfered through multiple implants, thanks to the modeled denture (Figure 4a).

For the second load case (600 N force with a 5° buccolingual inclination on both molars), the splinted variant showed increased resistance to flexure. In contrast, the unsplinted design showed a significant concentration of load in the outermost implant (Figure 4b).

The results of the third load case (600 N force with a vertical component only applied on the first premolar) do not show great differences in equivalent stress distribution between the splinted and unsplinted variants. As the load is effectively transferred into the body of the implant directly beneath the first premolar, bending is minimized. Consequently, the splinting bar's contribution is diminished. The denture also helps to distribute the load, reducing disparities between the two variants (Figure 4c).

3.2. Stress Distributions in Bone

The differences in stress were more significant in bone. The distribution of minimum principal (compressive) stress for the unsplinted design had proven to be inferior to the splinted design as the load concentrated into one of the implants and the bone had a severe stress concentration at one of the implants' apices (Figure 5). This was mainly manifested in the posterior region of the maxilla.

Conversely, the splinted setup effectively prevented excessive implant displacement with the use of bars. Compressive stresses were significantly reduced for all load cases and primarily concentrated in the vicinity of the implants' axes in the posterior region (Figure 5c).

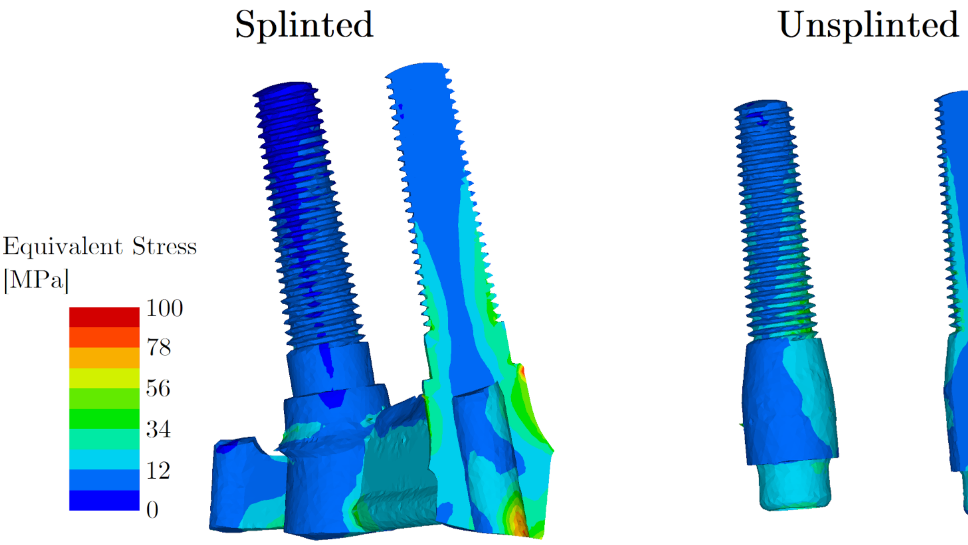
4. Conclusion

The results of this study show that the splinted variant provides a favorable, more even stress distribution. The values of stress are also lower in the analyzed load cases for the splinted variant, which confirms the null hypothesis.

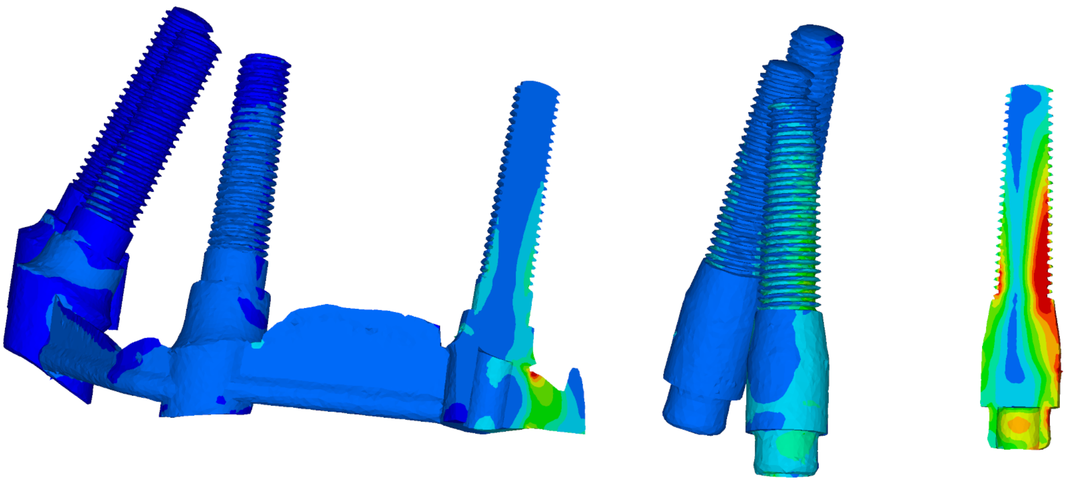
Since masticatory forces are transferred through the dental restoration, splinting offers a range of benefits in implant-supported rehabilitations, including improved resistance to lateral loading and prosthetic component fractures [19].

This numerical study concludes the following:

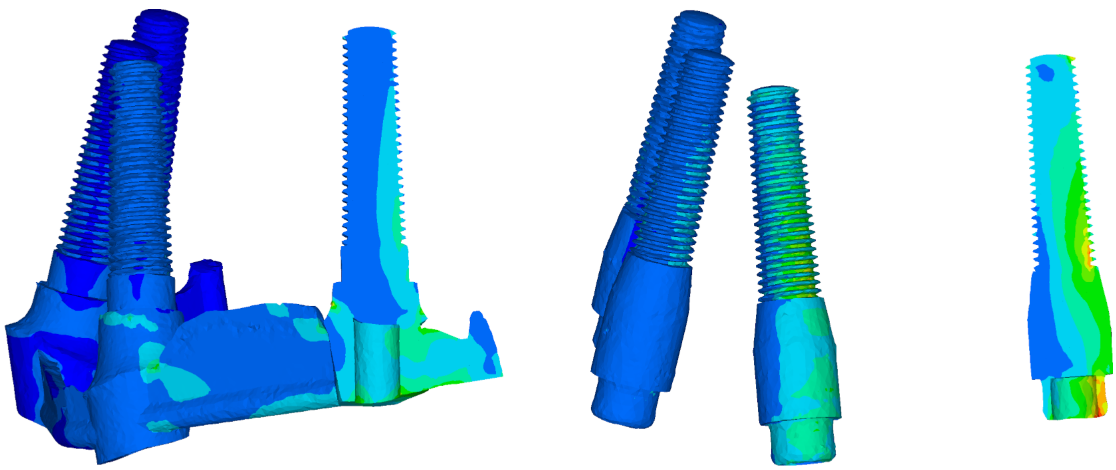
- Stress distribution in implants loaded in the frontal region (both incisors) shows a comparable pattern for both variants with values of equivalent stress being comparable and the differences negligible.



(A). First load case.

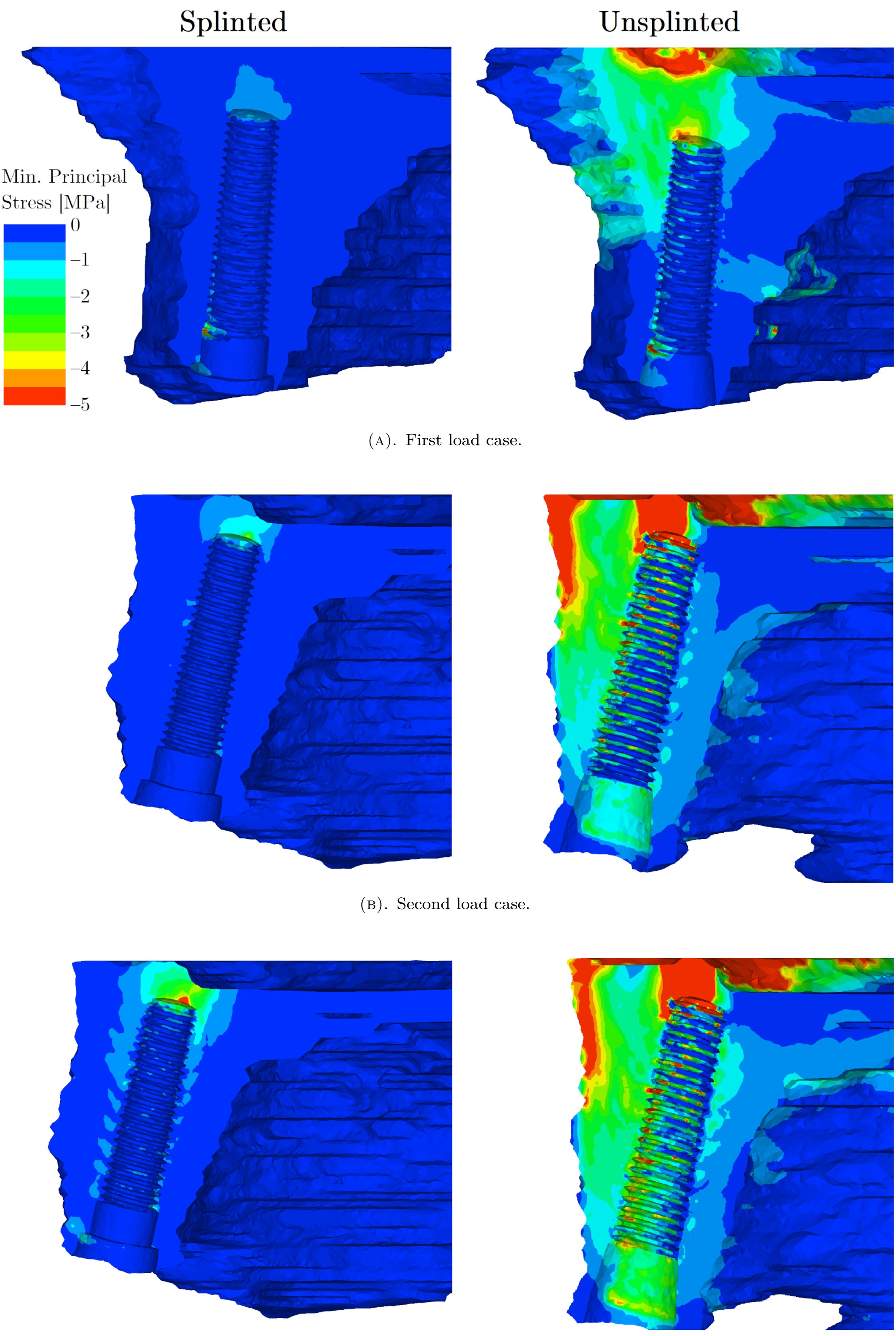


(B). Second load case.



(C). Third load case.

Figure 4. Isolines of equivalent (von Mises) stress normalized across all images. Left column – the splinted variant, right column – the unsplinted variant. All images display sections of the implant assemblies [4].



(a). First load case.

(b). Second load case.

(c). Third load case.

Figure 5. Isolines of minimum principal (compressive) stress normalized across all images. Left column – the splinted variant, right column – the unsplinted variant. All images display sections of bone in the buccolingual direction [4].

- Distal load applied on both molars shows the splinted variant distributes the load more evenly compared to the unsplinted variant and shows less bending in implants. On the other hand, load was concentrated to the outermost implant in the unsplinted variant.
- Force applied in the distal region on the first premolar did not create any significant stress concentrations in implants as the load was transferred solely into the body of the implant directly under the load and the effect of splinting was reduced.
- Compressive stress in the maxilla was inferior for the unsplinted variant with peaks of stress in the posterior region, namely around the implants' apices.
- The splinting effect played a significant role in preventing excessive implant displacement and bending and as a result, compressive stresses were less concentrated and had lower peaks for the splinted variant.

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