ORIGINAL ARTICLE

Effects of Palatal Plate Loading on Mucosa Development in Three-dimensional Finite Element Models

Tomoka Omori[1], Yuji Sato[2], Noboru Kitagawa[3], Osamu Shimodaira[4], Akio Isobe[5], Naoya Takamathu[6], Satomi Tanaka[7]

Abstract

Aim: The aim of this study was to verify the stress distribution associated with the thickness and elastic modulus of the palatal mucosa by three-dimensional finite element models of a dentulous subject and a pseudopalatal plate at pain onset after loading with a clenching force.

Materials and methods: The subject was a 35-year-old man with a dentulous jaw. Fourteen measurement sites were designated on the subject's palatal mucosa, and the mucosal thickness and load amount at pain onset were measured at each site with an ultrasonic thickness gauge and a strain gauge. These data were used to calculate the elastic modulus. Next, a pseudopalatal plate was created from scanning resin and photographed using cone-beam computed tomography. Three-dimensional finite element analysis (FEA) software was used to construct the pseudopalatal plate part. In addition, measurements of the actual mucosal thickness were added as elements to the mucosal surface of the pseudopalatal plate part. It was configured with the elastic modulus values of the palatal mucosa part. The load was the clenching force at the onset of pain (111 N cm) based on a previous study.

Results: The conventional and optimized models showed greatly different stress distributions. In addition, thick areas of the palatal mucosa were more susceptible to influence from the elastic modulus, while in the thin areas, stress generation was not related to the elastic modulus.

Conclusion: Differences in thickness have a greater impact on stress distribution than differences in elastic modulus. Thus, the results demonstrated the importance of building a model based on actual measurements of the thickness of a subject's palatal mucosa.

Keywords: Elastic modulus, Palatal mucosa, Pseudopalatal plate, Stress distributions, Three-dimensional finite element models, Ultrasonic thickness gauge.

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Introduction

Japan is a rapidly aging society, and since good-quality denture prostheses are essential for improving the quality of life, there is an increasing demand for denture therapy among elderly people.[1] However, evaluations of denture-related aspects are subjective in nature, indicating the need for a mechanism to obtain more accurate data.

The contact of the denture with the masticatory epithelium from the palatal mucosa in the hard palate causes physical stresses on it, which are tolerated due to the presence of the underlying lamina propria.[2] Therefore, objective evaluations of the properties of the denture-bearing mucosa are important in appraisals for denture therapy. Thus, a system to simultaneously measure the changes in load and mucosal thickness until the occurrence of pain can be useful for designing and optimizing dentures for patients.[3]

Three-dimensional finite element analysis (3D-FEA) can be used to estimate the internal dynamic stress, which is normally difficult to measure with experimental analysis. This technique has been used to assess the internal stresses and strains of dentures and denture-bearing mucosa, becoming a mainstream method of biomechanical analysis in the dental field.[4–6] A wide variety of physical data, such as stress, distortion, and displacement, can be obtained by a single analysis. These features, combined with the ease of configuration compared to other biomechanical examinations, make 3D-FEA an ideal method for kinetic analysis of the complex mucosa.

Previous 3D-FEA studies used homogeneous models that did not take into consideration the differences in thickness and elastic modulus throughout the mucosa (hereinafter referred to as conventional models).[4–7] However, to ensure better fit of the dentures, models that are optimized to the thickness and elastic modulus at different sites on the mucosa (hereinafter referred to as optimized models) need to be constructed. Therefore, in previous studies, optimized models were used to analyze the thickness and the elastic modulus simultaneously, and assessed the pain thresholds (pressure, subsidence, and compressibility) in dentulous[8] and edentulous patients.[9]

However, to apply this optimized system clinically, measurements would need to be performed by using a device that could conform to the actual shape of the denture. For this purpose, it was developed a maxillary palatal plate-form device that could simultaneously measure the clenching force and subsidence of the palatal mucosa at the onset of pain in dentulous subjects.[10] Moreover, in addition to actual measurements, analyzes of simulations are also useful for efficiently and objectively evaluating the various areas of the denture-bearing mucosa, which can be

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performed by 3D-FEA of the distribution of stress on the oral mucosa at pain onset.

Thus, the purpose of this study was to use 3D-FEA with an optimized model of the palatal mucosa and a model of the pseudopalatal plate area from a maxillary palatal plate-form for a simultaneous measurement device. Palatal mucosal stress distributions at the onset of pain from loading of clenching force were compared in a conventional model (uniform thickness and uniform elastic modulus), a uniform thickness model, and a uniform elastic modulus model.

Materials and Methods

Study Subject and Measurement Sites

This study was approved by the Ethics Committee of Showa University (approval number 2014-036), ethically conducted in accordance with Declaration of Helsinki. The subject provided informed consent for participation.

The subject was a 35-year-old man with a dentulous jaw and no obvious palatal protuberances or palatal mucosal abnormalities who had undergone measurements of palatal mucosal subsidence and clenching force at pain onset in a previous study.[10] Fourteen measurement sites were determined between the mesial side of the left and right maxillary first molars and the distal side of the left and right maxillary second molars (Fig. 1).

Calculation of Elastic Modulus

A device developed and improved by Takeuchi et al.[3] and Isobe et al.[8] for simultaneously measuring the load and mucosal thickness was used to measure the amount of load until pain onset and evaluate the changes in the palatal mucosal thickness before and after loading at the measurement sites. These data were used to calculate the elastic modulus.

The relational expressions used when pressure was applied using an ultrasonic thickness gauge probe with area A and load F are as follows:

$$P = F / A$$

$$C = S / T \times 100$$

$$E = P / C \times 100$$

where—

F	Load	N
A	Area of the ultrasonic thickness gauge probe	7.065 mm^2
T	Thickness of the oral mucosa before loading	mm
S	Subsidence	mm
P	Pressure	MPa
C	Compression ratio	%
E	Elastic modulus	MPa

Constructing the Three-dimensional Finite Element Model

Configuring the External Shape of the Pseudopalatal Plate Part

Tanaka et al.[10] developed a device that could simultaneously measure the load on the maxillary palatal plate and the thickness of the mucosa (hereinafter referred to as the simultaneous measurement device) and used it to observe the changes in palatal mucosal thickness from a clenching force applied until pain onset. This device consists of a pseudopalatal plate that is in contact with the palatal mucosa and subsides from the actual clenching force, a small compression load cell, and an ultrasonic thickness gauge.

For the three-dimensional finite element models in this study, models of the pseudopalatal plate part of the simultaneous measurement device and the palatal mucosa part were constructed. The range covered by the pseudopalatal plate part was the same as that of the device in the study by Tanaka et al.,[10] i.e., from the mesial left–right first molar to the distal left–right second molar. First, a pseudopalatal plate was manufactured from a resin contrastable in scanning radiograph (Fig. 2). This was fixed to a cone-beam computed tomography (CBCT) device and photographed at 90 kV tube voltage and 5 mA tube current with 0.125 mm slices. The CBCT data were used in the 3D-FEA software to construct a three-

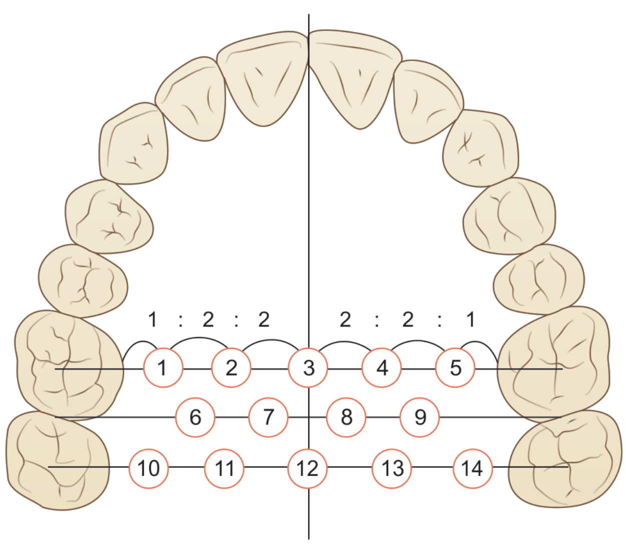

Fig. 1: Measurement sites

Fig. 2: Pseudopalatal plate with the scanning resin

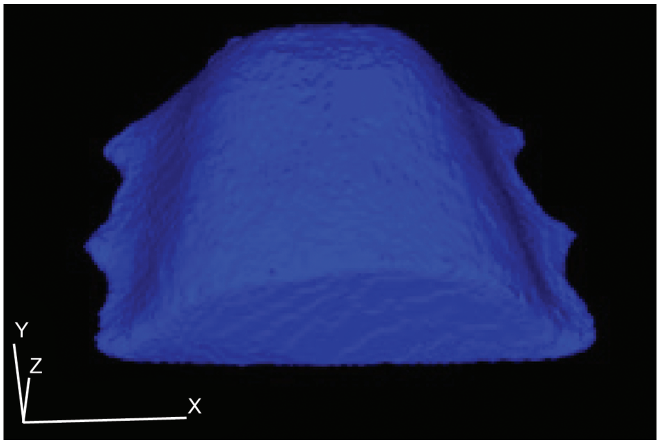

Fig. 3: Pseudopalatal plate part assessed using three-dimensional finite-element analysis software

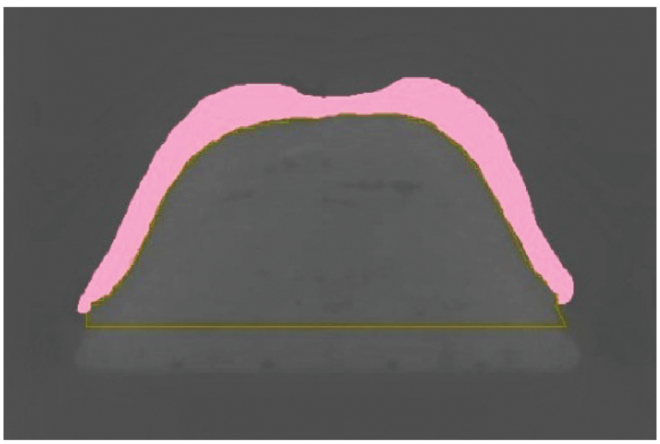

Fig. 5: Mucosa part assessed using three-dimensional finiteelement analysis software

dimensional finite element model (hereinafter referred to as the FEA model) of the pseudopalatal plate part (Fig. 3).

Thickness Configurations for the FEA Model of the Palatal Mucosa Part

While setting the external shape of the FEA model of the palatal mucosa part, the thickness values of the palatal mucosa of the optimized model and uniform elastic modulus model were configured. The mucosal surface of the FEA model of the pseudopalatal plate part was divided into 14 segments corresponding to the measurement sites, to which elements of actual thickness values were added (Fig. 4). Furthermore, the boundaries between the segments were edited to be smooth (Fig. 5).

Next, the thickness values of the FEA models of the palatal mucosa parts of the conventional model and uniform thickness model were configured. Thickness was set to 2 mm based on a study by Ogawa et al.[11] Uniform 2 mm thickness elements were added to the mucosal surface of the pseudopalatal plate parts.

Mesh Creation

The mesh was in the shape of a tetrahedron with 97,507 nodes and 526,725 total elements. The pseudopalatal plate part and the palatal mucosa part were both homogeneous, isotropic linear-elastic structures.

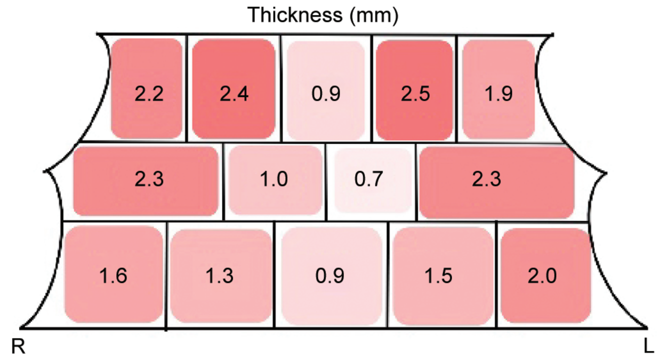

Fig. 4: Actual values of mucosal thickness

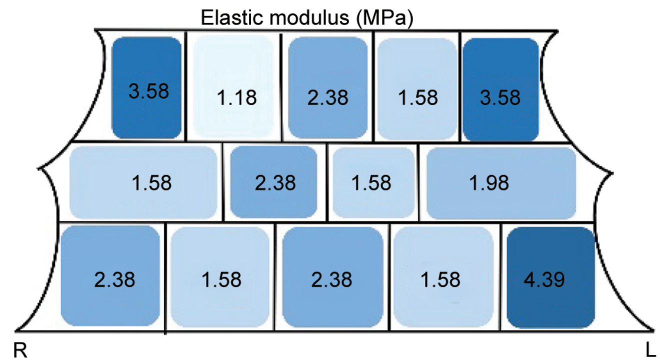

Fig. 6: Actual values of the elastic modulus

Conditions for the Analysis

Physical Property Configurations

For the physical properties of the FEA models, the moist resin was applied for the pseudopalatal plate part, with the elastic modulus set to 2,650 MPa[12] and the Poisson ratio to 0.3.[13] For the palatal mucosa part of the optimized model, the elastic modulus values were calculated from the actual values. The borders among the 14 segments were interpolated with the front–back–left–right mean values (Fig. 6). The elastic modulus values for the uniform thickness model were also calculated from the actual values. For the conventional model and the uniform elastic modulus model, the elastic modulus of the palatal mucosal part was set to 3.5 MPa based on the study by Isobe et al.[8] and the Poisson ratio was set to 0.4 based on the study by Takamatsu et al.[14]

Load Conditions

To create the same conditions as those used in the simultaneous measurement device developed by Tanaka et al.,[10] a load perpendicular to the center of the pseudopalatal plate part was applied. The load of 111 N cm was used as the clenching force that caused the subject pain (Fig. 7).

Constraint Conditions

The uppermost surface of the palatal mucosa part was considered fully constrained, assuming adhesion to the maxilla (Fig. 7).

Boundary Conditions

Adhesion conditions were assumed for the boundary between the pseudopalatal plate part and the palatal mucosa part.

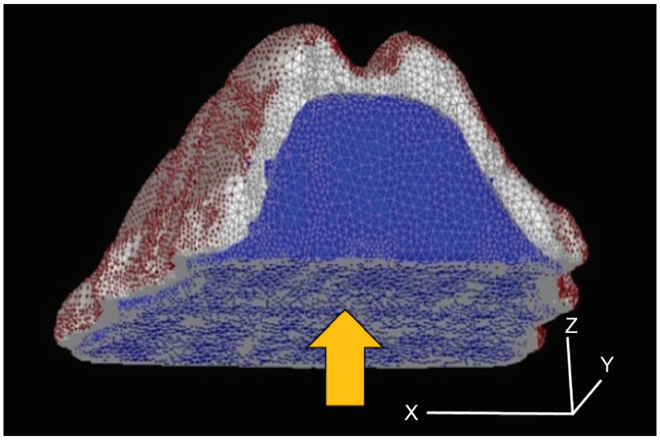

Fig. 7: Load constraint condition

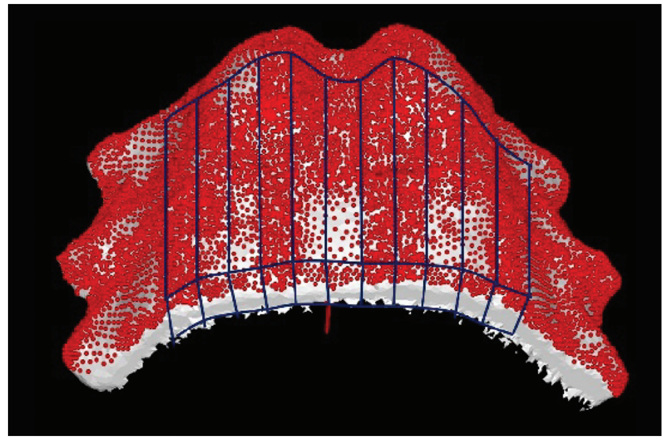

Fig. 8: Analysis area

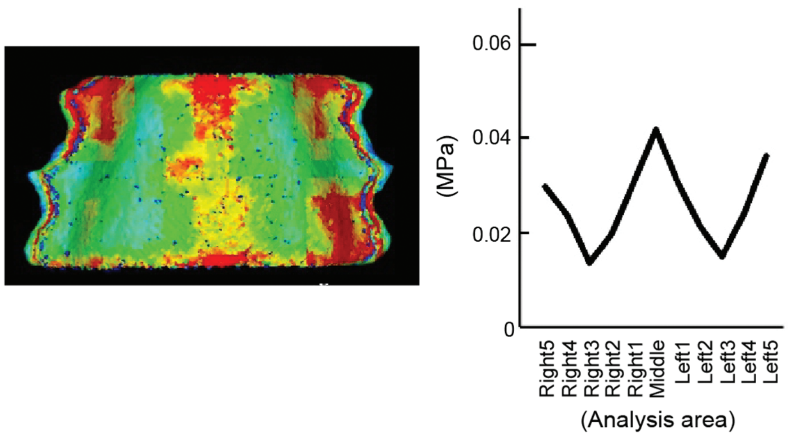

Fig. 9: Optimized model

Area of Analysis

To objectively evaluate the stress generated on the mucosa, the area of analysis was divided into 11 small regions of 3 mm width. The mean stress observed in each small region was used as the stress value for that small region (Fig. 8).

Results

Stress Distribution of the Optimized Model

The scalar distribution map of von Mises stress for the optimized model can be observed in Figure 9 and Table 1, which show the von Mises stress values for each area of analysis. Thin areas in practically the entire central palate, principally in the anterior region of the central zone, and areas with a large elastic modulus on the lateral palate, mainly on the right side and anterior left side, exhibited high stress values.

Comparison between the Conventional and the Optimized Models

The scalar distribution map of von Mises stress for the oral mucosa model was developed to compare the uniform thickness and uniform elastic modulus models (conventional models) with the optimized model (Fig. 10), represented, respectively, by dashes and continuous line. In association with the data registered in Table 1, it was possible to verify the von Mises stress for each area of analysis. After comparing both groups, the differences in stress values varied for the lateral regions and were greater in the conventional model and smaller in the central zone, showing a stress distribution completely different from that verified with the optimized model.

Comparison of the Uniform Thickness Model and the Optimized Model

Scalar distribution maps of von Mises stress in each area of analysis are presented (Fig. 11 and Table 1). Stress distribution approximated in the lateral regions between the different models, although the distribution in the central zone showed substantial differences, with the higher values observed for the optimized model.

Comparison of the Uniform Elastic Modulus Model and the Optimized Model

In each area of analysis, the distributions of the von Mises stress (Fig. 12 and Table 1) exhibited the most similarity between the groups, with a little more stress in the uniform elastic modulus model.

Discussion

Previous studies have evaluated the features of denture-supporting tissues under pressure with different settings.[3,8–10] Therefore, the utilization of specific devices appears to be suitable for acquisition of an adequate form of the denture, which is essential for clinical

Table 1: The von Mises stress for each area of analysis

	Right 5	*Right 4*	*Right 3*	*Right 2*	*Right 1*	*Midline*	*Left 1*	*Left 2*	*Left 3*	*Left 4*	*Left 5*
Optimized model	0.0304	0.0243	0.0145	0.0206	0.0313	0.0425	0.0313	0.0221	0.0158	0.0249	0.0369
Conventional model	0.0333	0.0334	0.0275	0.0255	0.0254	0.0253	0.0267	0.0269	0.0277	0.0339	0.0387
Uniform thickness model	0.0415	0.0324	0.0205	0.0217	0.0238	0.0247	0.0218	0.0205	0.0192	0.0356	0.0505
Uniform elastic modulus model	0.0332	0.0330	0.0259	0.0312	0.0405	0.0539	0.0432	0.0345	0.0286	0.0315	0.0349

application. Thus, this study used three-dimensional finite element models in a dentulous individual with a pseudopalatal plate to correlate the stress distribution at pain onset after loading with a clenching force with the thickness and elastic modulus of the palatal mucosa.

In the field of mechanical studies, FEA has been applied for obtaining stress and strain measurements, explaining the distribution inside the structures as a result of internal and external forces.[15] Conversely, limiting factors like points of contact with the palatal mucosa and the number of elements involved can reduce the perfect reproducibility of the FEA model shape.[15] Therefore, the stress distribution in 3D-FEA provides an overall insight into the palatal mucosa as a first-order analysis in the initial stage of the mechanical evaluation of the denture-bearing mucosa,[16] dividing a model into minute elements that can be configured in detail with load conditions and physical properties, introducing assessment of temporal elements with non-linear or dynamic analysis, to create more accurate simulations, similar to other studies.[8–10]

Specific 3D-FEA software was used in this study, allowing the construction of the shape of the model directly from CBCT images converted into digital imaging and communications in medicine (DICOM) data. The image acquired by CBCT shows superior quality with respect to the exposure dose, resolution, slice thickness, and reduction of artifacts than multi-slice computed tomography.[17] The use of radiograph impermeable scanning resin makes it possible to easily obtain CBCT images of the pseudopalatal plate, which allowed the model to be constructed faster and in complex shapes. Thus, it was considered a suitable method for constructing FEA models of the shape of the dentures worn by subjects. Nonetheless, the literature has shown that the assessment of periodontal soft tissue by CBCT is difficult due to the limited contrast, with the exception of the palatal mucosa, which is close to air, besides precluding accurate measurement of the palatal mucosa thickness and being a noninvasive method.[18]

Afterward, for the sake of efficiency, the model in this study was constructed based on thickness values in 14 segments, and it yielded results that suggest the importance of thickness configurations that conform to actual conditions in the analysis of stress distributions. Furthermore, regarding thickness, while CBCT and magnetic resonance imaging (MRI) can be used to capture the morphology of the palatal mucosa, there is no easy method for measuring elastic modulus. Therefore, going forward, CBCT and MRI should be used to investigate ways of reproducing the continuous, organic thickness of the mucosa, rather than just at certain sites or segments.

For this experimental test, we selected a dentulous man to avoid any interference and validate the methodology and risk of bias, since the mucosal thickness differs between young and old people (range, between 2.0–3.1 mm and 3.2–3.7 mm), and also between genders, with women showing thinner mucosa.[19] We also assumed adhesion between the pseudopalatal plate and the palatal mucosa and a better stabilization compared to the edentulous condition, allowing us to not consider the stress caused by the horizontal movements and the friction or creep between these parts. Setting contact conditions for the boundary to evaluate friction or creep would have created complex morphologies on the boundary surfaces of the pseudopalatal plate and palatal mucosa parts, which were divided into several partitions. This would have generated errors in the analysis, making it impractical. Furthermore, in this study, perpendicular compression stress on the palatal mucosa was

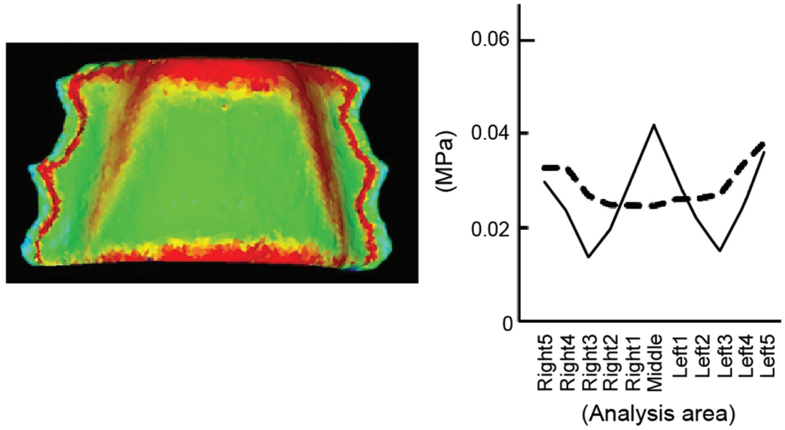

Fig. 10: Conventional model

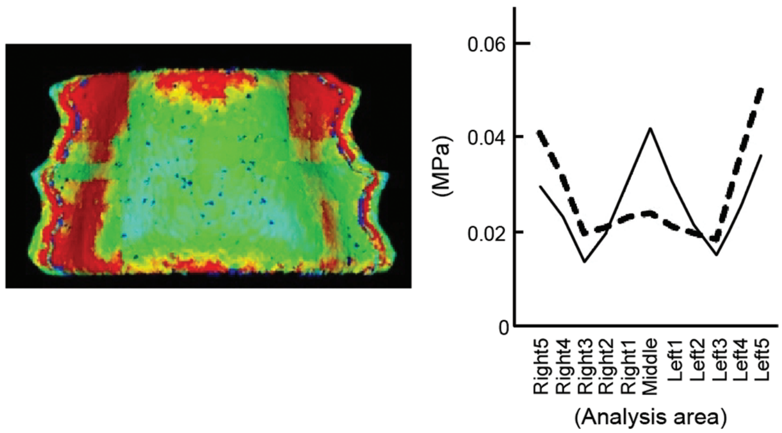

Fig. 11: Uniform thickness model

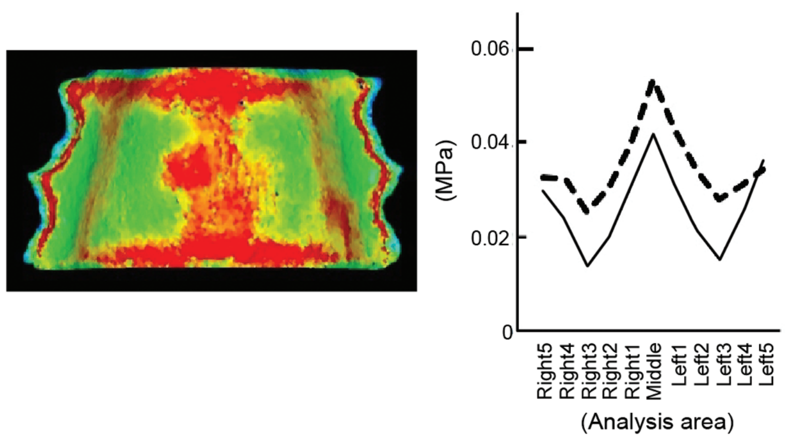

Fig. 12: Uniform elastic modulus model

evaluated based on the application of a perpendicular load on the pseudopalatal plate part.

Furthermore, this study showed that thicker areas of the palatal mucosa were more susceptible to influence from the elastic modulus, while the elastic modulus showed no relationship to stress generation in the thinner area. Related with areas of thinner mucosa, they exhibited less mucosal subsidence under loading and were less influenced by the elastic modulus, generating more stress. In contrast, thicker areas exhibited more subsidence and were more impacted, which diffused and distributed the stress within the mucosa. Similarly, these results were observed by Song et al.[20] and Barão et al.[21] with thicknesses from 3 to 5 mm (increasing 11% the stress value), and Ozyilmaz et al.[22] when they referred to the stress distribution to the mucosa, showing lower stress in thinner mucosa.

Controversially, the study by Barão et al.[21] obtained a lower stress value in a 3 mm mucosa than a 1 mm mucosa, which is in concordance with the findings reported by Tanino et al.,[23] consequentially presenting a less elastic modulus. Then, the results of the present study showed that in comparison to the uniform thickness model, the stress distribution of the uniform elastic modulus model was closer to that of the optimized model.

Thus, the findings of the present study suggest that differences in thickness have a greater impact on stress distribution than differences in elastic modulus. That is, even with a uniform elastic modulus, if the thickness is configured accurately, the stress resistance of the denture-bearing mucosa to pressure can be analyzed in a way that reflects actual conditions.

Moreover, this study can provide a broader understanding of the stress and elastic modulus, and it opens a pathway to guide future studies to focus on the amount of palatal mucosal subsidence and investigate methods of optimizing the design of relief ranges and improves the clinical application of the model, mainly for edentulous subjects.

Conclusion

Within the limitations of this study, it can suggest that the configuration of the mucosal thickness has particular importance in the analysis of stress distribution of denture-bearing mucosa while loading a pseudopalatal plate model, which was objectively evaluated through the stress distribution of the palatal mucosa at pain onset by using an FEA model.

Presentation/Support Information and Titles

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