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Assessment of stress distribution and pain perception in knife-edge ridge with different thicknesses of acrylic soft denture liner: A static linear three-dimensional finite element analysis

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Abstract: Previous studies on stress distribution and pain perception in dentures with acrylic soft liners have focused solely on axial loading, neglecting the oblique forces involved in mastication. This study aimed to evaluate stress distribution and pain perception with varying acrylic liner thicknesses (1 mm, 2 mm, and 3 mm) under both axial and oblique loads. An in-silico study was performed employing static linear three-dimensional finite element analysis. The von Mises stress color contour plot was used to analyze stress distribution. The study found that without an acrylic soft denture liner, the highest stress distribution occurred at the anterior buccal shelf under axial load and at the posterior lingual vestibule under oblique load. With a 1 mm liner, peak stress was observed at the canine ridge crest under axial load and at the molar 3 ridge crest under oblique load. At 2 mm, peak stress was noted at the incisive ridge crest under axial load and at the molar 3 ridge crest under oblique load. With a 3 mm liner, peak stress distribution was found at the incisive ridge crest under axial load and at the retromolar pad area under oblique load. The 1 mm acrylic soft denture liner provides optimal comfort and pain reduction, effectively distributing stress in axial and oblique chewing loads, whereas thicker liners may reduce the denture's ability to resist deformation, leading to higher stress distribution and discomfort.
Keywords: *Acrylic soft denture liner, Finite element analysis knife-edge ridge, Pain perception, Stress distribution.*

1. Introduction

Edentulism represents an irreversible state of toothlessness, defined by the absence of natural teeth, which can compromise the integrity of the masticatory system, reducing phonetic and aesthetic functions and eliminating periodontal support [1, 2]. Globally, edentulism exhibits a high prevalence, affecting approximately 0.1–14.5% of individuals under 50 years and 2.1–32.3% of the elderly, with prevalence increasing with age [3]. Heat-polymerized acrylic resin complete dentures, commonly used as mucosa-supported replacements, restore essential masticatory, phonetic, and aesthetic functions [4]. However, high failure rates and discomfort are common, often due to alveolar bone resorption and shifts in masticatory load forces [5].

Alveolar bone resorption, influenced by both systemic and local factors, progresses gradually, occurring at a higher rate in the mandible than in the maxilla [6, 7]. A common mandibular pattern, the knife-edge ridge, frequently causes discomfort due to its narrow peak acting as a fulcrum during mastication, leading to denture instability and excessive stress on underlying soft tissues; subsequently,

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resulting in pain [8, 9]. Uneven stress and pain on knife-edge ridge alveolar ridges can be managed with a soft denture liner, made of acrylic and silicone, which absorbs and evenly distributes stress across the residual ridge [10-12]. This cushioning material reduces pain perception, enhances denture comfort, and may also minimize alveolar bone resorption [13].

Various methods, both in vivo and in vitro, measure stress distribution under dentures [14]. In vivo methods cannot directly assess stress on ridge mucosa during chewing, while in vitro methods face challenges in replicating natural ridge shapes and are costly and time-consuming [14]. Finite element analysis is the preferred method, offering precise analysis of the biomechanical response of edentulous mucosa under complete dentures, while minimizing clinical and laboratory errors [15].

Numerous studies have assessed various acrylic soft denture liner thicknesses to evaluate stress distribution and pain perception using finite element analysis [16-19]. Previous study has shown that acrylic soft denture liner thickness of 1–2 mm effectively matches the mucosa's elastic modulus, distributing stress and reducing pain perception [16]. Furthermore, some studies suggest 2–3 mm is also effective, though excessive thickness may weaken the denture base [16-19]. To the best of author's knowledge, studies on stress distribution and pain perception in dentures using acrylic soft denture liners have mainly focused on axial loading, with no research evaluating both axial and oblique directions. Since mastication involves both, the aim of this study was to investigate stress distribution and pain perception in dentures with different acrylic soft denture liner thicknesses (1 mm, 2 mm, and 3 mm) under both axial and oblique chewing loads.

2. Methods

2.1. Study Design and Setting

An in-silico study was performed employing static linear three-dimensional finite element analysis, conducted from January to March 2024 at Outpatient Clinic of Prosthodontics, Dental and Oral Hospital, Medan, Indonesia and the Computational and Experimental Mechanical Systems Research Center, Universitas Sumatera Utara, Medan, Indonesia. The present study was conducted following the Reporting Guidelines for In-Silico Studies Using Finite Element Analysis in Medicine (RIFEM) [20] which are also applicable to dentistry. The present investigate stress distribution and pain perception in dentures with different acrylic soft denture liner thicknesses (1 mm, 2 mm, and 3 mm) under both axial and oblique chewing loads.

2.2. Software Used

The present study utilized AutoCAD version 2016 (Autodesk, San Francisco, California, USA), SpaceClaim Ansys R1 (Space Claim Corporation, Concord, Massachusetts, USA) and Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA) for both two-dimensional and three-dimensional modeling. Furthermore, Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA) was used for data analysis from simulation results. Dentsply Sirona Primescan® 2 Intraoral Scanner (Dentsply Sirona, Charlotte, North Carolina, USA), a handheld device, was employed for digital intraoral impressions.

2.3. Segmentation Process

Physiological impression-taking of the mandibular knife-edge ridge was performed to obtain a working model and fabricate a complete lower denture with bilateral balanced occlusion (Figure 1A). Cone beam computed tomography (CBCT) was performed on the patient's lower jaw, and a complete denture was scanned using Dentsply Sirona Primescan® 2 Intraoral Scanner (Dentsply Sirona, Charlotte, North Carolina, USA). The CBCT file was exported in DICOM format and converted to an STL file for modeling using AutoCAD version 2016 (Autodesk, San Francisco, California, USA) and SpaceClaim Ansys R1 (Space Claim Corporation, Concord, Massachusetts, USA) (Figure 1B). A model of the knife-edge ridge was constructed with mucosa of 1 mm thickness, following the ridge's anatomical shape (Figure 1C, Figure 1D, and Figure 1E). The complete lower denture was scanned and

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reconstructed using SpaceClaim Ansys R1 (Space Claim Corporation, Concord, Massachusetts, USA), considering parameters such as base thickness and design (Figure 1F). The resulting denture models were categorized with and without acrylic soft denture liner, applied with varying thicknesses and following the intaglio design. Acrylic soft denture liner was also modeled to cover the intaglio surface of the denture base. The present study defines axial and oblique masticatory load directions as loads applied parallel to the tooth's axis and at an oblique angle, respectively, perpendicular to the transverse plane, with a force of 100 N. This load was directed at the fossae of the mandibular first premolar, second premolar, and first molar. Stress distribution on the knife-edge ridge represents the highest stress distribution produced by the applied force, distributed along the ridge.

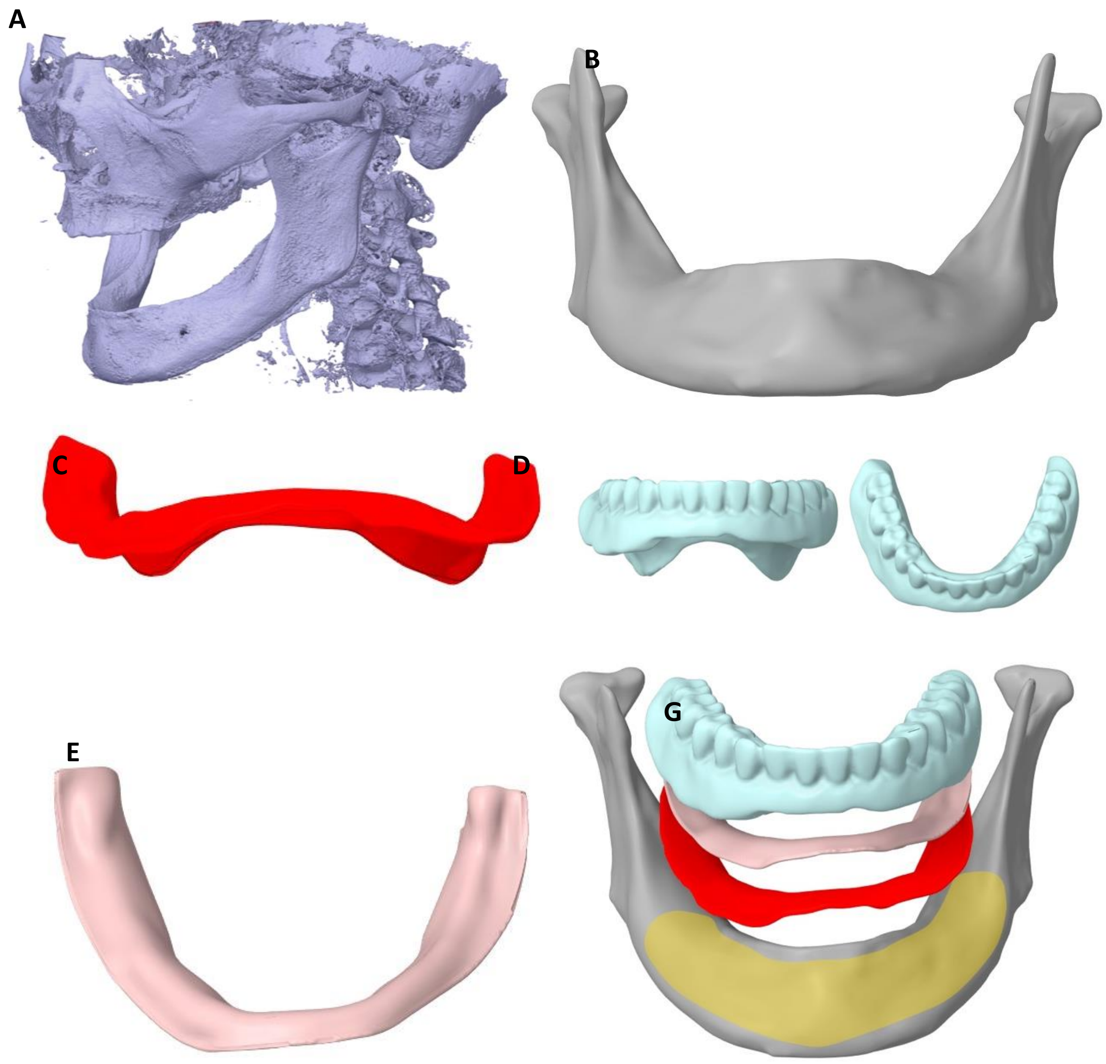

Figure 1.
Detailed three-dimensional model design from cone beam computed tomography (CBCT) (A), including the mandibular knife-edge ridge (B, C, D), mucosa with 1 mm acrylic soft denture liner thickness (E), and the complete denture structure (E), with the unified integration of alveolar bone, mucosa, liner, and denture components (E).

2.4. Convergence Test

Loading was applied according to the occlusal points in bilateral balanced occlusion. Boundary conditions were defined to determine the loading and constraints applied to the model in order to obtain the output results from the finite element analysis. In this static linear analysis, all materials were gradually applied up to the maximum value, after which the load remained constant (time-independent), and the finite element analysis calculations continued until convergence (no variation).

2.5. Nodes And Elements

Material properties were assigned to each component based on the data input during the engineering data phase. The coefficient of friction between the denture and mandibular knife-edge ridge was also incorporated at this stage. Each model was constructed using Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA) for meshing. Mesh generation involves dividing the analysis continuum into discrete parts, or finite elements (Figure 2). In the present study, tetrahedral meshing was applied to the models, with the mandibular ridge and complete denture without acrylic soft denture liner consisting of 674,537 nodes and 388,482 elements, acrylic soft denture liner 1 mm with 734,979 nodes and 421,854 elements, acrylic soft denture liner 2 mm with 737,772 nodes and 423,434 elements, and acrylic soft denture liner 3 mm with 745,747 nodes and 428,596 elements.

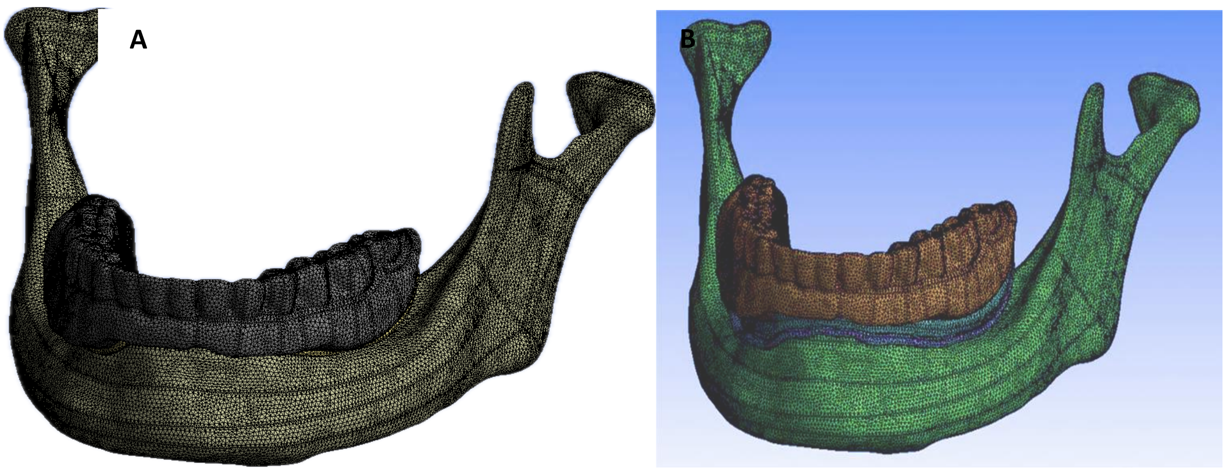

Figure 2.
Comparison of meshing models: without the acrylic soft denture liner layer (A) and with the acrylic soft denture liner layer (B).

3. Dimension

Fixed support was applied to the muscle insertion area, specifically the temporomandibular joint (Figure 3). Displacement restrictions were imposed along the X, Y, and Z axes (three-dimensional mode), with the occlusion concept used in the complete denture being bilateral balanced occlusion, where the angle of the denture components was set at 33°. A 100 N masticatory load was applied to the areas of highest chewing force (first premolar, second premolar, and first molar) in both axial (Figure 3A) and oblique (Figure 3B) directions.

3.1. Model Simulation

The present study conducted simulations following the stages of engineering data, geometry, model, set-up, solution, and results, organized into a project framework. These properties influence the stress and strain distribution on the denture structure, soft denture liner, gums, and bone. The properties utilized in the present study included Young's modulus, Poisson's ratio, and the coefficient of friction. Young's modulus represents the stiffness of a material, while Poisson's ratio indicates the volumetric response of a material to mechanical load. During this phase, STL files of the mandibular knife-edge ridge and complete denture were imported into the Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA). Subsequently, the design of the mandibular ridge, mucosa, acrylic soft denture liner, and complete denture was integrated into the model.

3.2. Mechanical Validation

The present study assessed the mechanical properties of denture components: the Polymethyl methacrylate base with a Young's modulus of 2000 MPa and Poisson's ratio of 0.3, and acrylic with a Young's modulus of 2940 MPa and Poisson's ratio of 0.3. The alveolar ridge mucosa was assumed to be 1 mm thick, with compact bone having a Young's modulus of 20,000 MPa, cancellous bone 2000 MPa, and mucosa 5 MPa. The acrylic soft denture liner had a Young's modulus of 1.5 MPa and Poisson's ratio of 0.35. The friction coefficient between the denture and mucosa was 0.16.

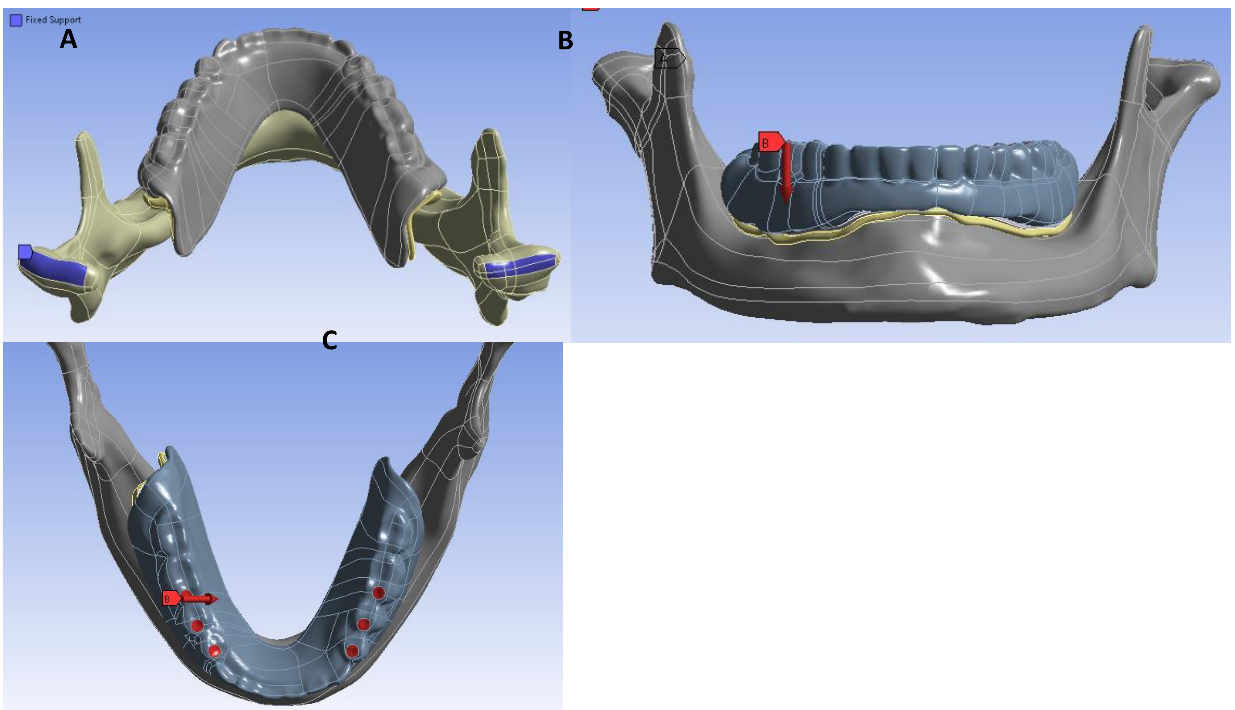

Figure 3.
Model setup: fixed support (A), axial load (B), and oblique load application (C).

3.3. Study Variables

The present investigate stress distribution and pain perception in dentures with different acrylic soft denture liner thicknesses (1 mm, 2 mm, and 3 mm) under both axial and oblique chewing loads. The von Mises stress color contour plot (red, orange, yellow, green, and blue) was used to analyze stress distribution, with the highest stress reported at specific anatomical locations. Red represents the highest stress point, while blue indicates the lowest stress point. Pain perception was measured using Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA), occuring when stress exceeds the pain perception threshold of 0.630 MPa.

3.4. Stress Distribution and Pain Perception Analysis

After the numerical input and load simulation were performed, stress distribution and pain perception assessment were carried out. Stress distribution in the finite element analysis was more clearly observed through the post-processing results of the equivalent von Mises stress, based on a color pattern (red, orange, yellow, green, and blue). Red represents the highest stress point, while blue indicates the lowest stress point. Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA) allows for the analysis of stress distribution based on discrete principles and deformation when the model is subjected to static loads. The von Mises stress color contour plot was utilized to analyze the stress distribution. Pain perception occurs when stress exceeds the pain perception threshold of

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0.630 MPa, as measured using Ansys software version 17.0 (ANSYS Inc., Canonsburg, Pennsylvania, USA) and reported in MPa.

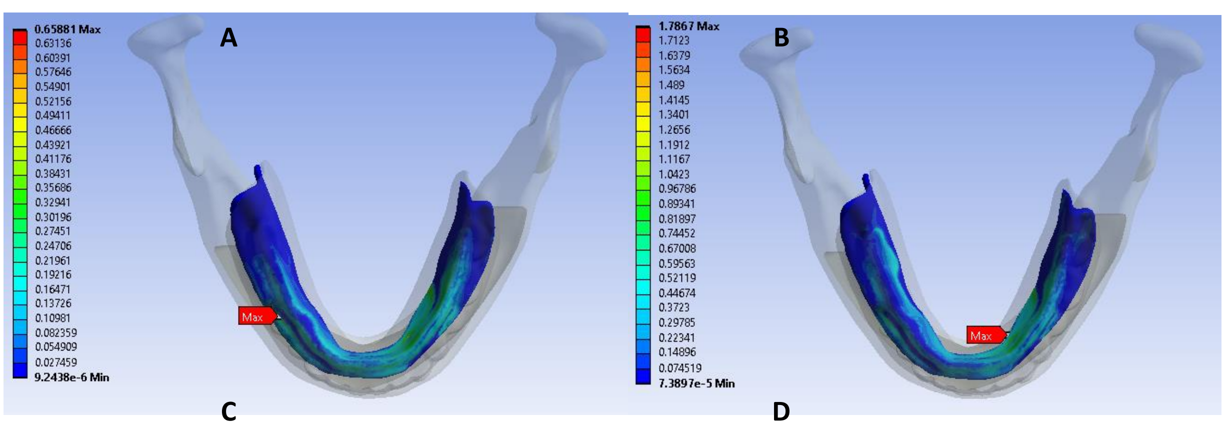
4. Results

The highest stress distribution and pain perception in dentures with different acrylic soft denture liner thicknesses (1 mm, 2 mm, and 3 mm) under both axial and oblique chewing loads are presented in Table 1. The present study found that, without the acrylic soft denture liner, the highest stress distribution was 0.658 MPa under axial load at the anterior buccal shelf (Figure 1A) and 1.786 MPa under oblique load at the posterior lingual vestibule (Figure 1B), both exceeding the pressure pain threshold of 0.630 MPa. With a 1 mm acrylic soft denture liner, the highest stress distribution was 0.349 MPa at the canine ridge crest under axial load (Figure 1C) and 0.628 MPa at the molar 3 ridge crest under oblique load (Figure 1D), both below the threshold. With a 2 mm acrylic soft denture liner, the highest stress distribution was 0.392 MPa at the incisive ridge crest under axial load (Figure 1E) and 0.701 MPa at the molar 3 ridge crest under oblique load (Figure 1F). The stress distribution under oblique load exceeded the threshold, indicating potential pain perception at this location. With a 3 mm acrylic soft denture liner, the highest stress distribution was 0.430 MPa at the incisive ridge crest under axial load (Figure 1G) and 0.811 MPa at the retromolar pad area under oblique load (Figure 1H). The stress distribution under oblique load surpassed the threshold, indicating the potential for pain perception at this location.

Table 1.
Highest stress distribution and pain perception across groups.

ASDL thicknesses	Axial		Oblique	
	Highest stress distribution	**Pain perception (MPa)**	**Highest stress distribution**	**Pain perception (MPa)**
Without ASDL	Anterior buccal shelf	0.658	Posterior lingual vestibule	1.786
1 mm ASDL	Canine ridge crest	0.349*	Molar 3 ridge crest	0.628*
2 mm ASDL	Incisive ridge crest	0.392*	Molar 3 ridge crest	0.701
3 mm ASDL	Incisive ridge crest	0.430*	Retromolar pad	0.811

Note: Abbreviation: ASDL, Acrylic soft denture liners.
*Below the threshold of 0.630 MPa



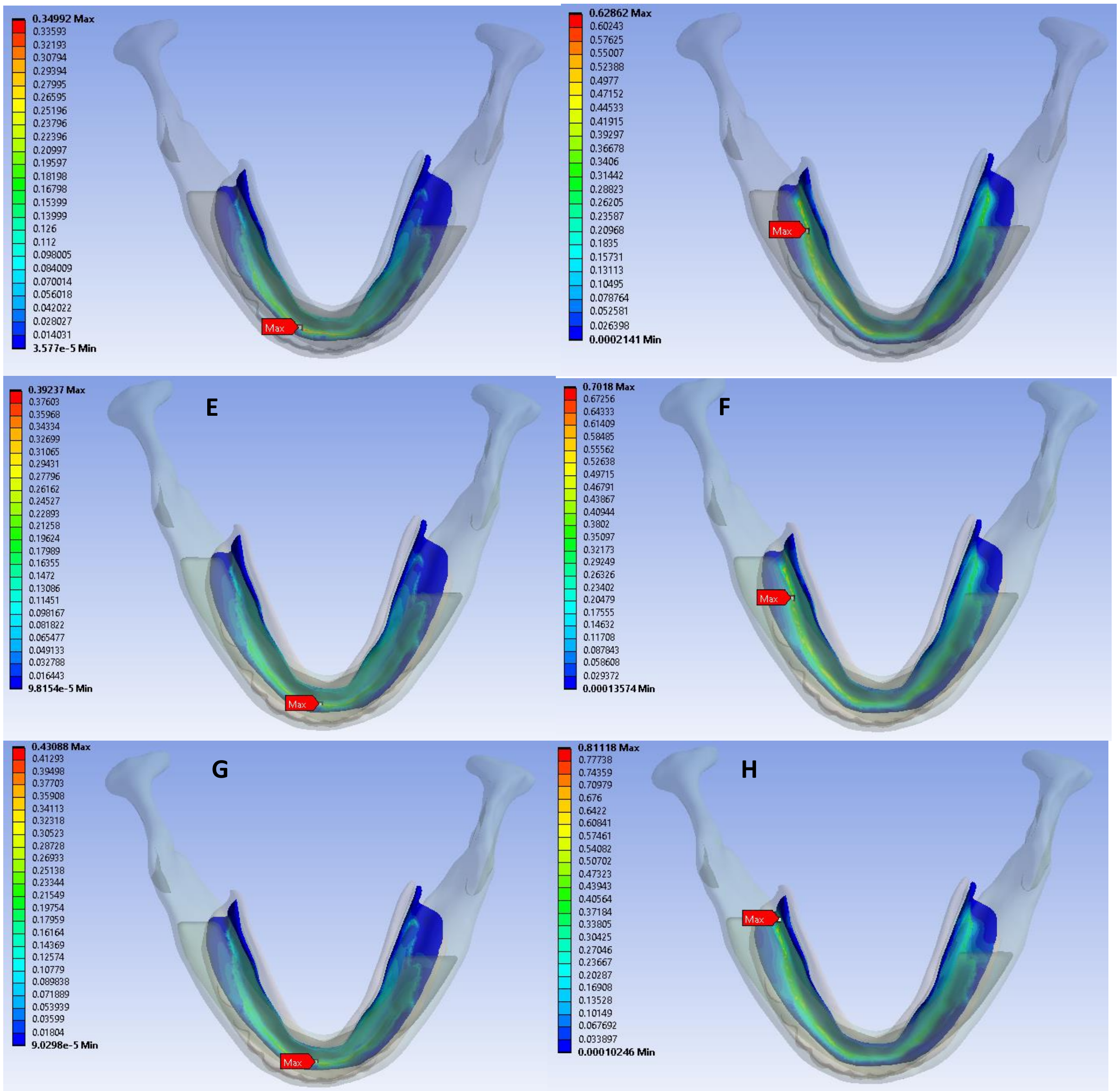


Figure 4.
Stress distribution on the knife-edge ridge under the denture: A) without ASDL, axial load; B) without ASDL, oblique load; C) 1 mm ASDL, axial load; D) 1 mm ASDL, oblique load; E) 2 mm ASDL, axial load; F) 2 mm ASDL, oblique load; G) 3 mm ASDL, axial load; H) 3 mm ASDL, oblique load.

5. Discussion

In the present study, the highest stress distribution under axial load was observed in the buccal shelf without the acrylic soft denture liner, while with 1 mm, 2 mm, and 3 mm liners, it shifted to the anterior knife-edge ridge area. Under oblique load, the highest stress consistently occurred in the posterior denture area, regardless of the liner thickness. This difference can be attributed to the fact that the axial load direction is the primary and most frequent direction during mastication and aligns with the tooth axis when the cusp tip of the tooth contacts the fossa [9]. Therefore, axial loads can occur in both the anterior and posterior areas. In contrast, oblique loads occur according to the cusp inclination

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on the posterior elements of the complete denture, which results in the load being directed only in the posterior area [21].

Without acrylic soft denture liner, in the present study, the highest stress distribution of 0.658 MPa occurred in the anterior buccal shelf, a primary mandibular stress-bearing area of dense cortical bone [13]. Masticatory forces were directly transferred from the denture to the underlying mucosa, with axial loads inducing significant stress concentration due to the perpendicular alignment and density of the buccal shelf [22]. The stress is aligned with the axial load direction, and although the highest stress distribution exceeds the average pressure pain threshold of 0.630 MPa, the pain perception is lower in the buccal shelf compared to other regions. Furthermore, in the present study, the highest stress distribution (1.786 MPa) occurred in the posterior lingual vestibule, which is twice as high as that under the axial load. The oblique load generates resultant forces that cause significant denture movement, and without an acrylic soft denture liner, the rigid denture base fails to absorb or resist deformation, resulting in higher stress distribution [18].

With a 1 mm acrylic soft denture liner, the highest stress distribution of 0.349 MPa was found around the canine ridge crest in the present study, which is lower than that without the acrylic soft denture liner. This demonstrates the cushioning effect of the 1 mm acrylic soft denture liner, which absorbs and distributes masticatory forces [13]. However, the small anterior surface of the knife-edge ridge limits this absorption, leading to the highest stress distribution in canine ridge crest [23]. Furtheremore, in the present study, the highest stress distribution remains below the pain threshold, preventing pain perception. Similarly, in the present study, the highest stress distribution (0.628 MPa) was observed around the molar 3 ridge crest. It is assumed that the molar teeth, as the primary chewing teeth, experience significant masticatory forces, and thus the highest stress distribution is expected in molar teeth [24]. This is approximately 65% lower than without an acrylic soft denture liner, indicating that the 1 mm thick acrylic soft denture liner is sufficient, as its viscoelastic properties improve the stability of the denture, allowing it to absorb and evenly distribute the deformation caused by displacement, release, and shifting from oblique forces [18].

For a 2 mm acrylic soft denture liner, under axial load in the present study, the highest stress distribution was 0.392 MPa at the incisive ridge crest, slightly higher than with the 1 mm acrylic soft denture liner. However, stress distribution remained below the pain threshold (0.630 MPa), and similar levels of comfort and pain reduction were observed for both 1 mm and 2 mm liners. Under oblique load, in the present study, the highest stress distribution of 0.701 MPa occurred at the molar 3 ridge crest, which is slightly higher than with the 1 mm acrylic soft denture liner. This increase may be attributed to the greater mucosal flexibility of the thicker acrylic soft denture liner, which reduces the denture base's ability to resist deformation, causing higher stress distribution and pain perception [18, 25]. However, increasing the liner thickness may weaken the denture base's mechanical strength. Excessive thickness is thus unnecessary for optimal denture performance.

With a 3 mm acrylic soft denture liner, under axial load in the present study, the highest stress distribution was 0.430 MPa at the incisive ridge, slightly higher than with the 1 mm and 2 mm liners. Under oblique load, the highest stress distribution occurred in the retromolar pad area, reaching 0.811 MPa in the present study. This may be due to the increased flexibility of the denture base wings, which reduces their ability to resist deformation from oblique forces [26]. While the stress distribution is still lower than without an acrylic soft denture liner, it exceeds the pain threshold in the present study, contributing to pain perception. The present study confirms that soft denture liners thicker than 2 mm slightly increase stress distribution due to the material's increased softness, reducing its ability to evenly distribute stress compared to 1 mm and 2 mm liners [18].

The findings of the present study suggests that a 1 mm acrylic soft denture liner is optimal for enhancing patient comfort and minimizing pain, as it effectively distributes stress from both axial and oblique chewing loads without exceeding pain thresholds. Thicker liners, while providing cushioning, may compromise the mechanical stability of the denture, leading to increased deformation and higher stress concentrations, which could result in discomfort. Therefore, dentists are suggested to consider using a 1 mm soft liner for patients with knife-edge ridges or similar anatomical features to balance comfort, stress distribution, and mechanical integrity.

A limitation of the present study is that the elastic modulus of the acrylic soft denture liner with varying thicknesses was assumed to be uniform, due to the lack of supporting literature. Additionally, the highest stress distribution values obtained do not represent the stress distribution in each individual denture support area but rather reflect the overall stress distribution across the entire denture support area. Future research could explore the long-term durability of various acrylic soft denture liner thicknesses under different masticatory forces and their effects on the soft tissue interface. Further studies could investigate the impact of liner material properties on comfort and functional stability over time. Additionally, researchs into the relationship between liner thickness, stress distribution, and patient-specific factors such as bone density and ridge morphology are necessary to enable more personalized treatment approaches.

6. Conclusion

The 1 mm acrylic soft denture liner provides optimal comfort and pain reduction, effectively distributing stress in axial and oblique chewing loads while preventing pain perception, whereas thicker liners may reduce the denture's ability to resist deformation, leading to higher stress distribution and discomfort.

Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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