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APPLIED RESEARCH

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Numerical study of the stress state on the oral mucosa and abutment tooth upon insertion of partial dentures in the mandible

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Abstract

The introduction of a removable partial denture onto the dental arch significantly influences the mechanical stress characteristics of both the jawbone and oral mucosa. The aim of this study was to analyze the stress state caused by biting forces upon insertion of partial dentures into the assembly, and to understand the influence of the resulting contact pressure on its retention behavior. For this purpose, a numerical model of a removable partial denture is proposed based on 3D models developed using computer tomography data of the jawbone and the removable partial denture. The denture system rests on the oral mucosa surface and three abutment teeth. The application of bite forces on the denture generated a stick condition on the loaded regions of the denture-oral mucosa interface, which indicates positive retention of the denture onto the oral mucosa surface. Slip and negative retention were observed in the regions of the contact space that were not directly loaded. The contact pressures observed in the regions of the oral mucosa in contact with the denture were below the clinical pressure pain threshold value for soft tissue, which potentially lowers the risk of pain being experienced by denture users. Further, the variation of the retention behavior and contact pressures across different regions of the denture assembly was observed. Thus, there is a need for adhesives or restraining mechanisms for the denture system in order to avoid bending and deformation of sections of the denture as a consequence of the applied bite force.

KEYWORDS

abutment tooth, contact pressure, pressure–pain threshold, Removable partial denture, residual ridge resorption.

1 | INTRODUCTION

Proper oral health is paramount to quality of life, and a growing area of interest for quality of life measures.[1,2] It is defined as the state in which individuals are not limited with regards to their capacity regarding biting, chewing, smiling, speaking, and physiological well-being.[3] The years of healthy life lost per 100,000 people from edentulous and severe tooth loss in the European Union has increased by 6.7% since 1990, at an average of 0.3% a year.[4] Furthermore, only approximately one half of adults aged 20–64 had not lost a tooth in 2011–2012.[5] To address the widely prevalent condition of tooth loss across the global population, dentures remain one of the most popular solutions for tooth restoration and are often supported by the remaining natural teeth, which act as abutments. Removable dentures continue to be important from the standpoint of cost, regardless of the level of comfort and lowered chewing effectiveness.[6] Two types of dentures are utilized- complete and partial. Partial dentures are typically held in place with clasps that attach to existing teeth. Kennedy classification is well-known for classifying dentures with regards to the various partial edentulous arches and their respective locations in the dental arch.[7] These clasps are generally made of metal and can wear away the contour of the natural tooth structure and surface. Dentures secured by these methods could possibly cause an increased risk of tooth wear and decay, especially in regards to the abutment tooth.[8] Additionally, the bulk of the documented reasons of denture discomfort arise from problems associated with the mastication of foods and poor retention of the denture.[9,10] Moreover, according to Szentpetery et al. (2005), the excessive loading of the soft tissues underneath a denture is responsible for a large proportion of denture wearers experiencing palpable pain.[11] According to Tanaka et al. (2004), "the pressure-pain threshold (PPT) is the limiting stress" beyond which the patient employing a denture experiences palpable pain in the tissue due to the applied occlusal forces that tissue experiences.[12] As such, the mucosal region's PPT is a significant determinant when evaluating the design and performance of dentures.[12,13] The PPT values for oral mucosa have been reported by multiple studies with variations. The intensity of pain recorded by Naganawa et al. (2013) puts the pain on a scale of 0–50–100[14] which can be utilized as a comparative tool.

The biomechanics of the denture and oral mucosa under bite forces are influenced by many problems associated with dentures, such as being ill-fitting.[15] From the work of Garrett et al. (1996) in the field of clinical studies, "basic variables such as occlusal forces, denture displacement, and foundation conditions are only barely acknowledged, if at all."[9] Further, according to Kydd et al. (1982), "the tissues in elderly persons takes many hours to recover from the effect of moderate mechanical forces,"[16] however, other studies have showed that such pressures from mechanical forces were "associated with a significant decrease in blood perfusion."[17] Compounding on this, removable partial denture (RPD) wearers often continue to bite and chew foods despite their discomfort. Therefore, pressures higher than the pressure pain threshold (PPT), could be detrimental to oral health particularly as the soft tissues and dental structures experience a highly complex and time dependent mastication loads and muscle forces.

According Röhrle et al. (2018), "the maximum voluntary bite force (MVBF) is a common parameter used to interpret the masticatory function and the MVBF may be used to access the performance of dental implants."[18] According to Ogata et al. (1995), the maximum mean value of occlusal forces was in the range of 65–110 N.[19] The occlusal forces from Tanaka et al. (2004) had a mean value of 97.1 N.[12] Retention and stabilization are significant performance parameters from the context of design both for full and partial dentures. Retention is described by[18] as "the force required for moving a denture from its base in the direction opposite to its insertion" and this retention behavior can be studied as a resistance to vertical dislodgement. This disengagement of the denture segment could be as a result of muscle forces or the bending moments generated in the denture segments as a consequence of the applied bite forces. Burns et al. (1995) also estimate the mean retention and stabilization force values for the dentures in case of the lower jaw.[20] Retention and stabilization, key design considerations, are also as per Müller et al. (2002) weakly correlated with chewing and occlusal forces.[21] Furthermore, such dentures develop other issues, such as slippage and movement, which over time potentially causes increased discomfort and irritation.[22] The contact pressure generated at the denture-soft tissue contact space due to biting forces can potentially influence these situations. This pressure should be distributed uniformly in order to avoid pressure points that may affect the tissues supporting the RPD.[23] Messias et al. (2019) also suggest that the pressure on the oral mucosa can induce bone resorption in edentulous regions.[24] As such, it is necessary to study the mechanical stress of the oral mucosa and dental structures under the application of biting forces when evaluating a denture system. The main objectives of this study were to develop a finite element model of the jawbone and RPD subassemblies, and to study the contact pressure upon the application of a bite force. Further, the study aimed to characterize the retention behavior at the RPD–oral mucosa contact space.

2 | MATERIALS AND METHODS

2.1 | Geometrical Modeling

This study involved 3D modeling of the jawbone, oral mucosa, and denture assembly components in order to carry out numerical simulations to study the resulting stress state upon the application of occlusal forces. CT scan data from a comparable anatomical model (SAWBONES EUROPE AB, Sweden, 216 16 Malmö, SKU: 1338–9) (Figure 1A) of the jawbone was used to develop the 3D model. One of the drawbacks of this approach is the root regions of the abutment tooth are absent and cannot be realized through CT, which is essential for observing the contact pressures between the tooth and jawbone. A slice from the computer tomographic scan illustrating the lack of root region of the molar abutment tooth is shown in Figure 1B.

Therefore, a second CT data set was needed to develop 3D volume image stacks for the three abutment teeth, namely the two canines and the 2nd molar. The segmentation was carried out using the software tool, AMIRA, so as to segregate the three specific tooth regions along with developing volume image stacks of all the CT scans. The third and final CT data set was for the denture assembly, comprised of three denture teeth segments with a denture base running through all of them. The RPD used in the study had three edentulous regions and classified as class A.I.P III under the Bailyn system of classification.[25] This data was used to reconstruct the denture teeth and denture base. The volume stacks developed using AMIRA are illustrated in Figure 2A–C.

The surface and CAD models for these volume stacks were developed using the CATIA software tool and individual 3D models were generated for the jawbone, oral mucosa, abutment teeth, denture base, and denture segments. A constant thickness of 0.3 mm was maintained for the oral mucosa based on the mean thickness value of 0.33 mm reported in the literature from the work of Stasio et al. (2019).[26] Figure 3(A) illustrates the jawbone sub-assembly with the abutment teeth and Figure 3(B) shows the denture sub-assembly. Figure 3c showcases the complete assembly used for further simulations in this study. To better visualize the stress state due to the applied bite forces, the abutment periodontal ligaments (PDLs) were incorporated into the model. The PDLs were included by using the contour of the three abutment teeth; based on this outer profile of the respective abutment tooth, a surface geometry was developed. This surface which represents the contact region of the tooth-PDL interface, was used to generate a volume model of the PDL. In this study, this was modeled with a constant thickness at 0.2 mm based on literature.[27] Figure 3d shows the sectional view with the molar PDL.

In this study, the jawbone, oral mucosa, and denture were modeled as isotropic materials. The material properties were adopted from,[28,29,30] and[31] for the jawbone, oral mucosa, and abutment teeth, respectively. The denture is made of PMMA and the denture base of surgical steel SS316; their material properties were also adopted from the literature.[32] The material laws and parameters used for all the components in this study are given in Table 1. The abutment PDLs were modeled as hyperelastic materials based on the parameters from the work of Huang et al. (2012).[33]

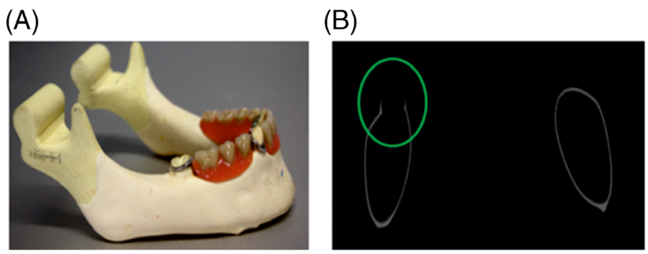

FIGURE 1 (A) The anatomical model (SAWBONES EUROPE AB, Sweden, 216 16 Malmö, SKU:1338–9) used for modeling the jawbone and oral mucosa and (B) a computer tomographic slice showing the absence of the root section of the abutment tooth in the sawbone model

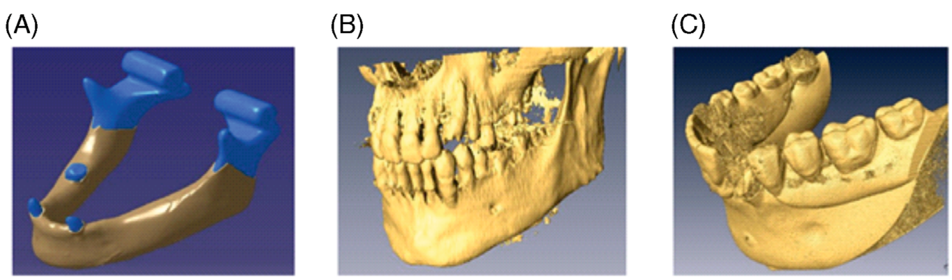

FIGURE 2 The volume stacks of the three computer tomographic (CT) datasets generated using the AMIRA segmentation module to be used for modeling the 3D geometries: (A) dataset for the jawbone and the oral mucosa, (B) dataset for the abutment tooth, and (C) dataset for the denture segments

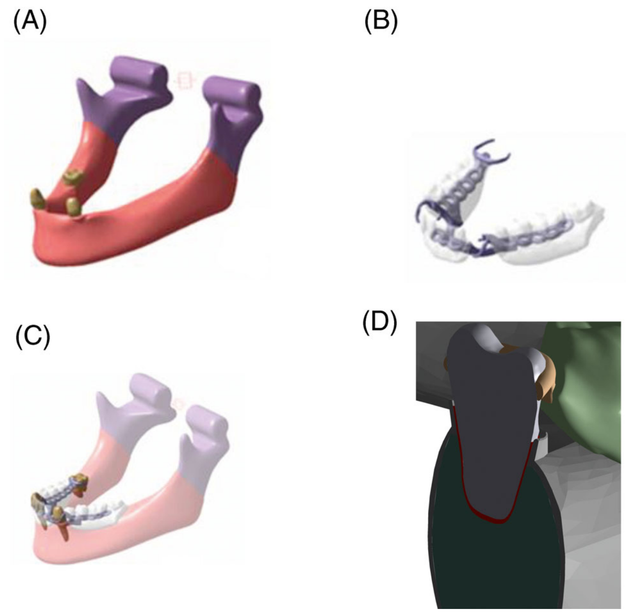

FIGURE 3 (A,B) The two major subassemblies and the mandibular region and the denture subassembly, respectively, (C) the 3D model of the mandible region with the denture system inserted into the assembly, and (D) sectional view showing the modeling of 2nd molar abutment PDL

TABLE 1 Material properties of the individual components

Material	Young's Modulus (MPa)	Poisson's Ratio
Jawbone[28]	2×10^4	0.3
Oral Mucosa[29,30]	8.33	0.4
Abutment tooth[31]	8.75×10^4	0.33
Denture base[32]	2×10^5	0.3
Denture teeth[32]	1.8×10^3	0.4

2.2 | Mesh Generation

A mesh convergence study was conducted to estimate the optimal mesh parameters for this study. A smaller representative segment of the entire assembly—consisting of one denture tooth, the molar abutment tooth, mucosa and the jawbone—was meshed with tetrahedral elements. The skewness of the mesh, which indicates the quality of the mesh and is defined based on the shape of the mesh elements, was used for analyzing the effect of the mesh size. Table 2 summarizes the mesh convergence study performed on the representative model. The skewness was quite large for coarser meshes and decreased substantially as the mesh was refined. Based on this, the entire assembly was meshed with a mesh size of 1 mm with an average skewness of 0.2859, which falls within the 'good' range as per ANSYS WB meshing guidelines.

A frictional approach was utilized for modeling the denture and mucosa contact space. A friction coefficient of 0.3 between the denture and oral mucosa was used based on sources in the literature.[34,35] Saliva plays a significant role in lubrication of the denture- mucosa contacts and results in extremely lower values regarding friction coefficient.[36] However, the effect of saliva is not considered here and the study assumes the ideal case of dried conditions. Higher friction coefficients have been reported in literature in the range of 0.3 to 0.4 in such ideal dried conditions.[34] The same was also implemented in this study. Similarly, a friction coefficient of 0.3 was used to model the contact space between the abutment teeth and the denture base. The contact regions were modeled based on augmented Lagrange method (ALM) in ANSYS software tool. The master surface was the denture compared to the soft tissue due to the difference in their assumed elastic moduli in this study, which is listed in Table 1.

TABLE 2 Orientation of the largest bite force at different regions along the right denture segment

	Orientation of the force (°)		
Parameter	1st Premolar	2nd Premolar	1st Molar
Sagittal angle (φ)	−26	−22	−15
Frontal angle (ψ)	−7	−8	−9

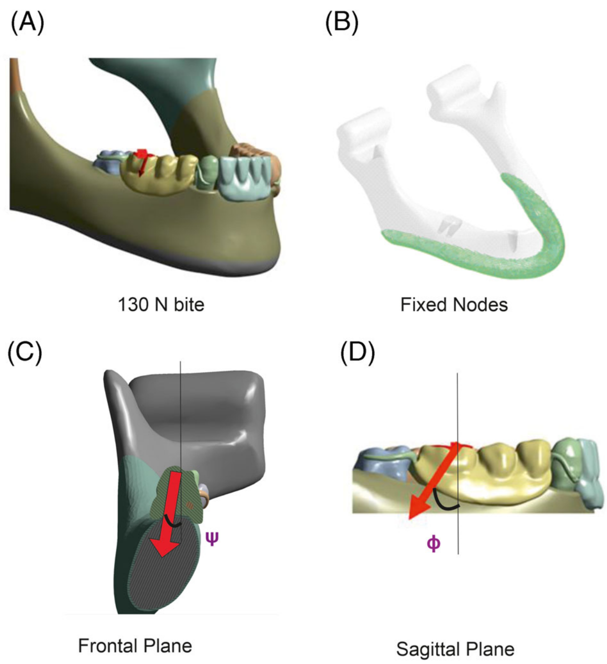

FIGURE 4 Illustration of the bite force and boundary condition employed: (A) force acting on the cusps of the 1st molar section in the right denture segment, (B) the fixed nodes modeled with Hypermesh tool, and (C) orientation of the force with respect to frontal plane ψ, and (D) with respect to the sagittal plane φ

2.3 | Boundary Conditions

A 130 N bite force was utilized based on the work of Chen et al. (2015) on the 1st molar section of the right denture segment.[34] The bite force was also applied eccentric and inclined to the tooth axis respectively. The orientations of the largest bite forces for various locations along the right denture segment are illustrated in Table 2, in terms of sagittal (φ) and frontal angle (ψ) subtended by the force vector. The orientations of the largest bite forces were adopted from the literature.[37] A fixed boundary constraint was prescribed on the lower surface of the jawbone in order to study the resultant stress upon the application of the bite forces. Figure 4A illustrates the bite force application and C, and D the corresponding orientation with the frontal and sagittal planes respectively. The fixed boundary condition assumed for the lower surface of the bone is illustrated in Figure 4B.

3 | RESULTS

The application of bite forces on the right denture segment induced contact stresses on the underlying oral mucosa at the contact space between them. The resulting distribution of contact pressure between the denture and oral mucosa is represented in Figure 5. The maximal contact pressure in the oral mucosa was 0.131 MPa and was observed directly beneath the region of load application on the denture; this value reduced gradually while moving away from the line of action of the load.

Figure 6A illustrates the state of the denture-soft tissue contact space during loading from a contact mechanical perspective. The right half of the denture remains in the inserted position under the influence of the applied occlusal load, indicating positive denture retention. On the contrary, the left denture mucosa contact space, which was not loaded directly, exhibited a 'near sliding contact condition' in some regions of the contact space. The left half of the denture is subjected to bending forces or lift-off in some regions as illustrated in Figure 6A. The negligible pressure distribution on the left denture region in Figure 6A further exhibits the lift off described above.

The deformation of the assembly under the action of oblique force with orientations described in Table 2 was also evaluated. Figure 6B illustrates the deformation of the denture base, with clasps resting on the abutment teeth. Positive values ranging from 0 to 0.305 mm were observed in the right denture segment. On the contrary, negligible or negative displacement, or lifting of the denture assembly is observed in the center and left denture segments, as indicated by the negative values of displacement.

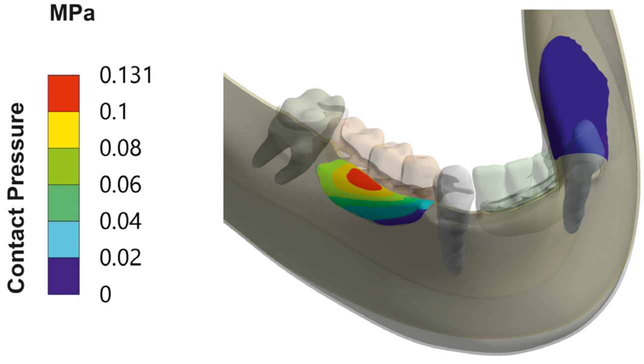

FIGURE 5 Contact pressures upon the application of 130 N bite force on the 1st molar tooth for the denture–mucosa interface

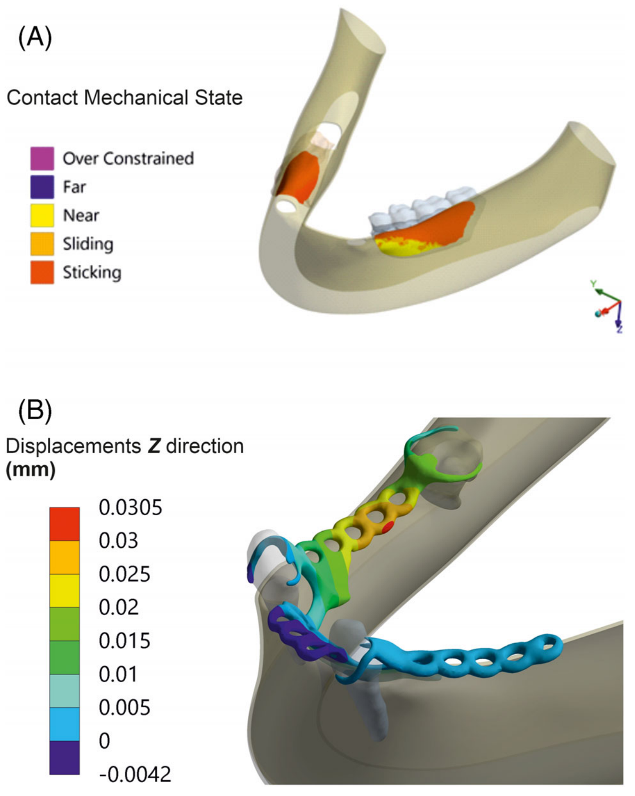

FIGURE 6 (A) Contact mechanical condition of the denture–mucosa contact region, illustrating denture retention under the influence of the applied load and (B) displacements observed in the denture assembly and abutment teeth upon the application of bite forces on the right denture segment with force orientations discussed in Table 2

Apart from the load transfer through the denture material onto the oral mucosa surface, a part of the applied load is also distributed through the abutment tooth. Figure 7 represents the contact pressure on the 2nd molar abutment tooth surface in contact with the denture clamp. The pressure distribution is the product of a complex set of bending moments resulting from the applied load; it can be clearly observed from the stress distribution of the positive and negative pressure zones. The outermost regions exhibit a negative pressure, which implies the bending in these regions could cause separation or sliding contact zones. On the other hand, there are large regions of positive pressure in the interior and central regions of the contact space, which indicates a sticking condition.

Finally, these stresses are transferred through the tooth body and into the jawbone. Figure 8A describes the contact pressure on the jawbone surface in contact with the 2nd molar abutment tooth, which is, one of the abutment teeth directly supporting the right denture segment. The bending moments on the abutment tooth results in positive and negative pressures in the contact space between the tooth and the jawbone. The contact pressure value is influenced by the

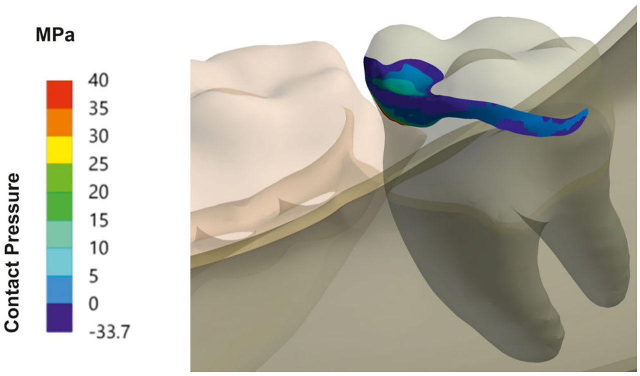

FIGURE 7 Contact pressure upon the application of 130 N bite force on the 1st molar tooth for the denture base–butment tooth interface

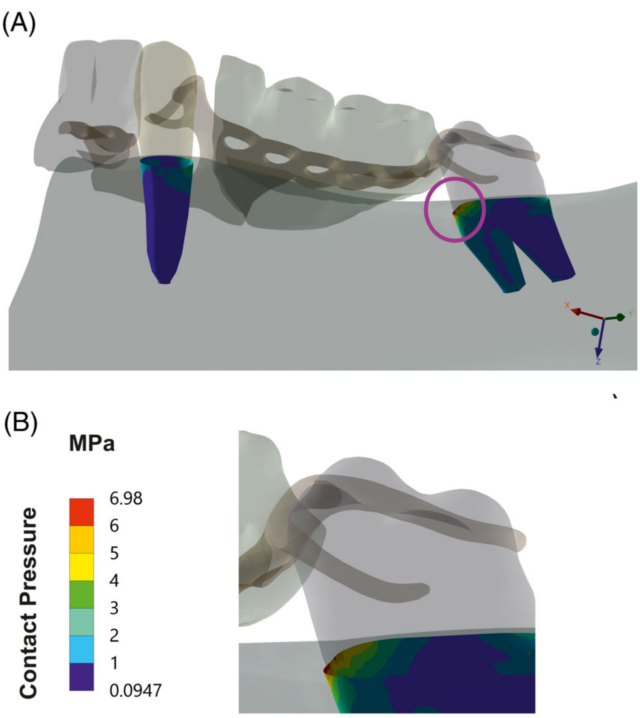

FIGURE 8 Contact pressure upon the application of 130 N bite force on the 1st molar tooth for the abutment tooth-jawbone interface at (A) the 2nd molar tooth and the right canine, and (B) the detail view showing the region of maximum pressure

PDL supporting the respective abutment teeth. The maximum contact pressure of 6.98 MPa was observed in the case of the molar abutment tooth as shown in Figure 8A and the location was closest to the bone surface as shown in Figure 8B. The pressure decreased from the bone surface to the root level of the abutment tooth. Figure 8C illustrates the corresponding contact pressures induced on the jawbone surface in contact with the right-sided canine tooth, and the second molar abutment tooth supporting the denture segment.

The contact pressure was lower for the canines, as they were farther away from the bite force location in the dental arch. The maximum pressure on the canine abutment tooth surface was in the range of 2–4 MPa.

4 | DISCUSSIONS AND CONCLUSIONS

The contact pressure on the oral mucosa, in the model has a direct influence on the retention of the denture in the proposed position in the dental arch. From the results it is evident that the right denture exhibits a sticking condition. This sticking condition is an outcome of the positive pressure on the contact space resulting from the applied load in this study. Thus, the right half of the denture remains in the inserted position under the influence of the applied occlusal load, indicating positive denture retention. On the contrary, the contact space between the left denture and oral mucosa, which was not loaded directly, exhibited a 'near sliding contact condition' in some regions. This contact space also experienced negligible, zero, or even negative contact pressures in different zones, which indicated that the contact space was not completely bound to the tissue surface as seen in the case of the right denture. The bite action on one side of the denture, the right denture segment in this scenario, results in the generation of bending moments at the center and left denture segments. These bending moments result in displacement or lift off of the denture from its resting position as seen in Figure 6B. The movement of the denture and the corresponding effects on the retention due to a direct application of the bite force on the cantilever side was not considered in this study. The study assumed that the action of the bite on the free side, results in comparable moments on the right denture, but that the presence of the supporting abutments on the opposite side would restrict displacement to an extent. As such, the retention behavior is also influenced by the contact pressures that are generated due to the loading pattern. The magnitudes of the displacements are small in this study and are limited by the single quasi-static load application method used. Multiple and cyclic load application would result in displacements of the denture assembly which cause discomfort to the user of the denture over a longer period of time. Additionally, Figure 6B indicates lift off in the vicinity of the contact between both the canine abutment teeth and the denture clasps. This displacement can also lead to wearing of the abutment teeth surface and lead to tooth loosening. The quality of the mesh plays a crucial role in the final output, and a mesh convergence study is essential in narrowing down the best possible mesh metrics for the specific numerical simulation. Such studies, though complex for geometries with free curvature profiles, can be performed as shown in previous reportings. Several methods are available, such as the one from Roda-Casanova et al. (2021),[38] but these methods require extensive CAD knowledge and are, from a computational standpoint, further complicated for large models such as that in this study. The mesh metric Jacobean, skewness, and aspect ratio have been used in the literature for a better accuracy of the results.[39] This study was based on the skewness and mesh quality of the elements, in order to choose the applied element sizes.

In point of fact, this displacement was mainly a result of the bonded contact definitions, which did not allow for the lifting up of the left denture even under the moment generated by the application of forces on the right denture, resulting in negative contact pressures being seen in this denture segment. The pressure distribution data on the soft tissue could be the focus of further research leading to methods for optimizing the model in order to have a better distribution of the stresses onto the soft tissue. The thickness of the mucosa varies from one region to another and the mean and highest values have been documented in the literature.[26,40] Zmudzki et al. (2012)[41] used a nice approach that modeled the mucosa and denture contact space and described the mucosal thickness values for such cases. The mean thickness of the buccal regions is reported throughout the literature to be around 0.3 mm and hence this was the value utilized in this study. Though there are several studies which consider higher thickness values,[42–44] the contact pressure is not directly influenced by the thickness parameter. Of course, the equivalent stress levels will be higher in our model due to the lower thickness value but this is expected to be closer to the realistic scenario as the buccal mucosa thickness was found to fall within this range. Furthermore, the mucosal thickness can potentially play a huge role in the stress state of the contact space and we feel that the variation in thickness must be incorporated into the simulations to fully capture this effect. However, to simplify model complexity, constant thickness is used in this work, as has similarly been done in the approaches of other groups. The model also shows the stress state of the abutment teeth, which is also a major region of interest in the case of RPDs. The contact pressure on the abutment tooth surface was greatly influenced by the abutment PDLs. Furthermore, as the thickness of the PDL varies from the bone level to the root, there could potentially be significant variation across the PDL. This cannot be captured by the constant thickness approach used in this study, but nevertheless, the advantages in terms of model simplification support this approach. Also, although the PDLs are crucial in respect to tooth loosening and stress state of the abutments, their role in influencing denture retention is limited due to their higher stiffness when compared to the oral mucosa.[45]

4.1 | Pressure-pain threshold

The pressure-pain threshold (PPT) is the limiting stress beyond which the patient wearing a denture experiences palpable pain in the relevant tissues due to the occlusal forces applied to it, such as during normal chewing and eating.[12] Building on this, the concerns of denture users regarding discomfort and pain sensation are also associated with denture related stomatitis.[23,46,47] The maximum contact pressure of 0.131 MPa, as observed in Figure 5 is below the PPT values for oral mucosa. PPT data from the literature for different sections of the oral mucosa indicates stresses in the range of 0.25 MPa in the buccal regions of the mandible, to around 1 MPa in the palatal regions.[13] The maximum contact pressure seen compares well to the derivations documented in the literature.[13,16,46,48–51] The contact pressure values observed in this study are also comparable to pressure pain threshold values seen in literature sources dealing with similar scenarios.[46,47]

However, negative pressure or lift off could result in discomfort or even distinct pain for the person employing such a denture design in the worst-case scenario. The magnitude of negative pressures and lift off observed could facilitate further research on optimizing the design of dentures to either reduce or eliminate these phenomena, which could affect the overall performance of the denture. The study was limited to the specific type of RPD as the stress response due to an applied bite force was the focus. Further, the focus of this study was limited to a quasi-static loading in terms of local bite force application on a specific region of the denture. The denture-oral mucosa contacts must be analyzed under a complex set of bending moments that result from transient load application, in order to estimate the realistic contact pressures generated during comminution of food. The long-term influence of the denture under transient loading conditions, such as residual ridge resorption, could not be studied here due to the assumption of isotropy and linear elasticity of the all the components used in the study.

This study attempts to capture the stress state of the dental structures upon the insertion of an RPD and specifically in the RPD–oral mucosa contact space. The results show a denture slip criterion or poor retention which can potentially cause discomfort to the denture wearers. However, the contact region could be studied in further detail by incorporating connecting mechanisms such as denture relining materials, which could play a role in stress relaxation as well. Additionally, studies could focus on the contact area of the denture on both the soft tissue and the abutment tooth as well as the ratio in which the load is transferred amongst the two, to identify ways to optimally lower the stresses on the soft tissue. The retention and stabilization of such partial dentures can possibly be improved with the application of denture adhesives or creams. These adhesives can restrict displacement and as a result lower the discomfort to denture wearers.

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CONFLICT OF INTEREST

The authors confirm that there are no financial and personal relationships with any other people or organizations that could inappropriately influence the content or the statements of the submitted article. All authors have read the final manuscript and confirmed this by email.

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