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RESEARCH AND EDUCATION

Finite element analysis of implant-assisted removable partial dentures: Framework design considerations

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ABSTRACT

Statement of problem. Connecting an acrylic resin base to both a metal framework and a rigidly fixed implant may affect the rotational displacement of the prosthesis during loading.

Purpose. The purpose of this finite element analysis study was to analyze the effect of connecting a denture base metal framework to an implant with the aim of decreasing the rotational movement of an implant-assisted removable partial denture.

Material and methods. A mesial occlusal rest direct retainer and a distal occlusal rest direct retainer were modeled and adapted to incorporate a modified denture base metal framework in the connection area for each model. The stress and deformation patterns of the prosthesis structure were determined using finite element analysis and compared for both situations.

Results. A maximum von Mises stress of 923 MPa was observed on the metal framework of the prosthesis with a mesial occlusal rest, and the maximum value was 1478 MPa for the distal occlusal rest. A maximum von Mises stress of 17 MPa occurred on the acrylic resin denture base for the mesial occlusal rest, and a maximum von Mises stress of 29 MPa occurred for the distal occlusal rest.

Conclusions. The distal occlusal rest direct retainer is stiffer than the mesial design and undergoes approximately 66% less deformation. The modified denture base framework with an I-bar and distal occlusal rest design provides more effective support to the acrylic resin structure. (J Prosthet Dent 2017;118:177-186)

The use of an implant with a tooth- and tissue-supported Kennedy class I removable partial denture (RPD) has been suggested as a way to reduce loading on the edentulous ridge.[1] Kennedy class I RPDs often fail to achieve patient satisfaction.[2] Although mandibular RPDs opposing a maxillary complete denture reduced the potential load on the extension base RPD and led to fewer patient complaints,[1] the downward growth of maxillary tuberosities, papillary hyperplasia, resorption of the premaxilla, overeruption of the mandibular anterior teeth, and resorption of the posterior mandibular ridge have been reported to be complications and are known as combination or Kelly syndrome.[3] In addition, the lack of any mandibular posterior tooth support compromises arch integrity, which also leads to combination syndrome.[4]

Implant rehabilitation has been shown to be an effective treatment for these conditions.[5] An implant-assisted removable partial denture (IARPD) could provide additional posterior support to prevent the resorption of the anterior maxilla and reduce the risk of combination syndrome.[6] However, fractured metal frameworks or acrylic resin denture base and late implant failure have been reported when attachments were incorporated into an IARPD.[7,8] The clinician needs to decide whether to design the prosthesis with contact between the implant and the IARPD on the acrylic resin or on a customized metal casting of a metal framework covering the attachments.[1] The influence of metal framework design modification on the prosthesis structure and its performance needs to be investigated. The purpose of this study was to evaluate the structural response and integrity as characterized by the induced stress and deformation of a modified metal framework design in the denture base area using finite element analysis (FEA).

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Clinical Implications

Redesigning the denture base framework of an implant-assisted partial removable dental prosthesis with an I-bar and distal positioning of the occlusal rest improve support during the loading of the acrylic resin denture base.

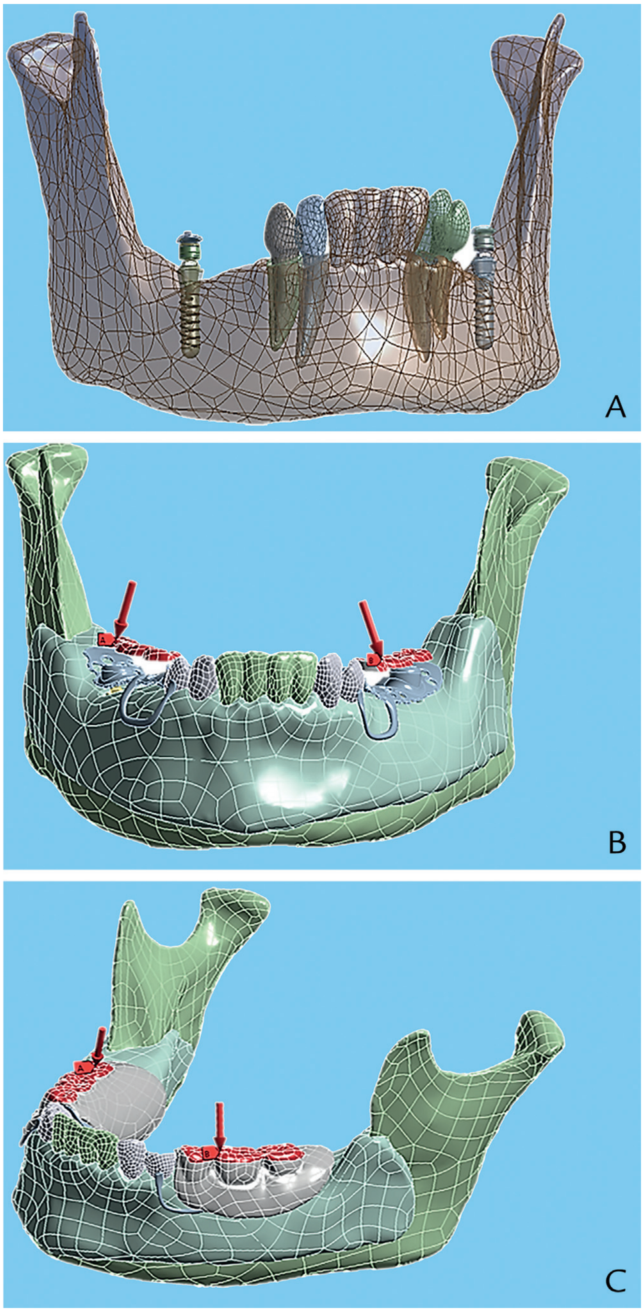

Figure 1. Assembled model of individual parts. A, Mandible, implant, teeth, periodontal ligament. B, Soft tissue, framework. C, Resin denture base and highlighted loading area.

MATERIAL AND METHODS

All components used in this study were created by computer-aided design (CAD) modeling that included individual part geometry creation, followed by an assembly process, as described in previous publications[9-11] (Fig. 1). Both the distal occlusal rest direct retainer and the mesial occlusal rest direct retainer metal framework models were modified to allow them to have direct contact with a titanium ball attachment.

The new denture base framework over the implant was modeled in CAD software (Solidworks 2008), using a combination of input data from the scanned geometry and CAD (geometric) models of the metal framework. This was subsequently exported as a Parasolid XT file. The matching missing section of the denture base metal framework was generated by creating a copy of the metal framework model. Likewise, the matching matrix section of the denture base metal framework was generated by creating a copy of the matrix and implant component model. The matrix feature was added to the metal framework and merged with the denture base metal framework. The parts were saved as multiple parts in Solidworks software to position different solid models as one entity in relation to the mandibular model. The matrices were accommodated in the prosthesis and aligned with the axis of the implant to avoid misalignment of the matrix position (Fig. 2).

Additional identical CAD (geometric) models of the prosthesis denture bases were required in order to analyze 2 types of metal framework designs. Thus, 2 copies of the denture bases were generated (1 for each metal framework design). A copy of the metal framework was made and used as a cutting tool to remove the common metal framework volumes from the prosthesis denture base. This procedure was repeated for each side of the denture base (Fig. 3). All final components were saved as separate solid part files and then exported as individual Parasolid XT files (Fig. 4).

The interaction between the individual components was specified through contact behavior. Contact surfaces between the teeth and periodontal ligament (PDL), PDL and mandible bone, mandible bone and soft tissue, implant body and mandible bone, resin denture base and metal framework were set to be perfectly bonded. Frictional contacts were modeled using the corresponding friction coefficients (μ) for all other component interfaces between the matrix and the implant ($\mu=0.36$), the occlusal rest direct retainer and the teeth ($\mu=0.1$), and the contact surface between the resin denture base and the soft tissue ($\mu=0.01$).[12,13] The PDL and dentin were considered elastic solids to incorporate realistic movements and deformations of the teeth. The interface between the root and PDL was considered bonded. The cementum layer was not considered as cementum and

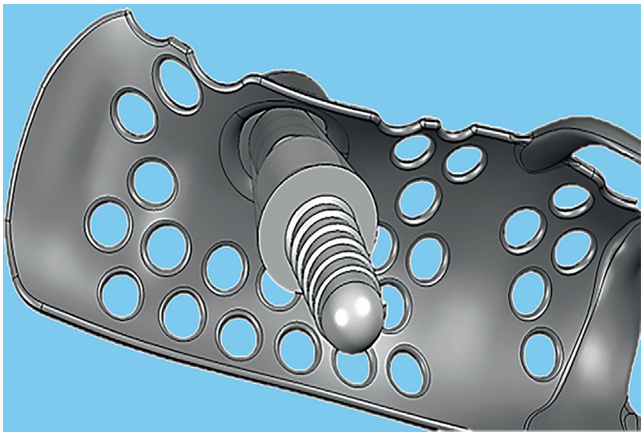

Figure 2. Titanium matrix inserted into modified denture base metal framework.

dentin have similar mechanical properties.[14] A tetrahedral mesh was generated with each node having 3 degrees of freedoms, the translations in 3 directions. The resulting finite element mesh had 216 780 elements and 376 975 nodes. The stress analysis was conducted with bilateral pressure applied on the surface of the teeth.

A static linear elastic FEA was used in this study. The bone was assumed to be transversely isotropic,[15,16] and all materials followed linearly elastic behavior, complying with the Hook law, using 2 physical properties, the Young modulus (E) and the Poisson ratio (ν) (Table 1). Although anatomic locations are fixed in oral structures, experimental data have shown that the mechanical properties of bone are nearly constant in the transverse plane.[15,16] Therefore, elastic deformation analysis under physiological loading can be conducted by assuming transversely isotropic linear elastic equations.[15,16] The overall stiffness of the bone was approximated by taking the average value based on the relative volume fraction of cortical and trabecular bone. The Young moduli values were 14.7 GPa for cortical bone and 0.49 GPa for trabecular bone, and the Poisson ratio for both the cortical and trabecular bone was taken to be 0.3 (Table 1).[17]

Table 1. Mechanical properties of materials

Characteristic	Titanium (Implant and Matrix)[a]	Acrylic Resin[b]	Cobalt Chromium[c]	Dentin[d]	Periodontal Ligament[d]
Young modulus (GPa)	110	2.20	211	41	68.90×10^{-5}
Poisson Ratio	0.33	0.31	0.30	0.30	0.45

[a] ITI product catalog. [b] Vertex product catalog. [c] Wironit product catalog. [d] Data from ref. 22.

The forces were applied on the model as equivalent surface pressures by evenly distributing them over the occlusal surface. The loaded areas were 198.92 mm^2 on the left and 183.01 mm^2 on the right side of the prosthesis. For the applied load of 120 N on each side, the pressures applied were 0.60 MPa on the left and 0.66 MPa on the right.

RESULTS

Stresses and deformations were determined in the different structures of the metal framework, the acrylic resin denture base, and the regions of the underlying tissue. The corresponding maximum values of the stresses were subsequently determined to assess the criticality and proneness to failure of the structures.

A maximum von Mises stress of 923 MPa was observed on the metal framework of the prosthesis with a mesial occlusal rest, and the maximum value of the stress was 1478 MPa for the model with a distal occlusal rest. Hence the maximum stress in the distal occlusal rest metal framework was approximately 60% higher than that in the mesial occlusal rest. In the IARPD with a mesial occlusal rest, the stress was highest where the lingual bar was connected to the denture base area (Fig. 5).

The stress pattern was distinct for the acrylic resin denture base structure on the framework for the distal occlusal rest direct retainer (Fig. 6). In the mesial

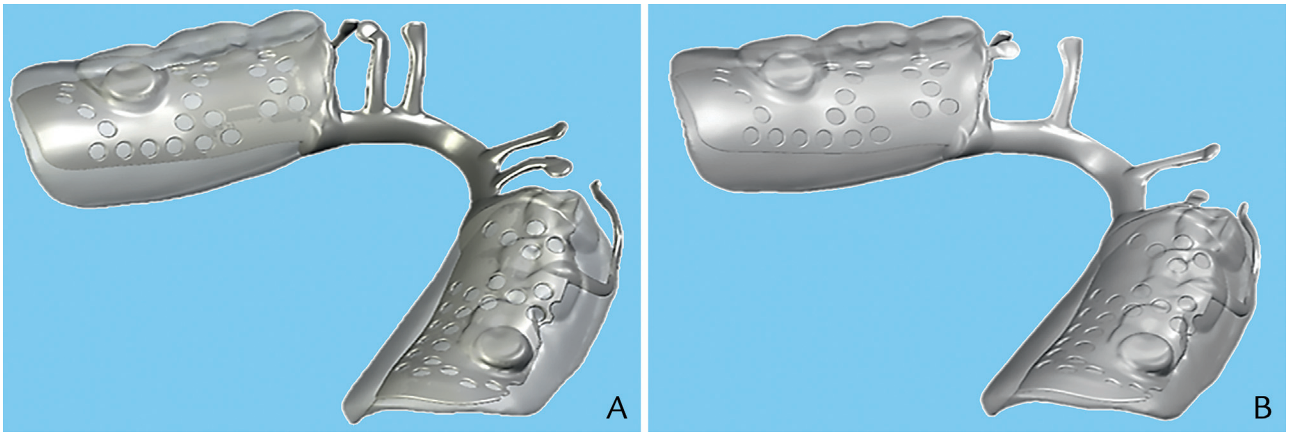

Figure 3. Implant-assisted removable partial denture with acrylic resin denture base inserted. A, Mesial occlusal rest. B, Distal occlusal rest.

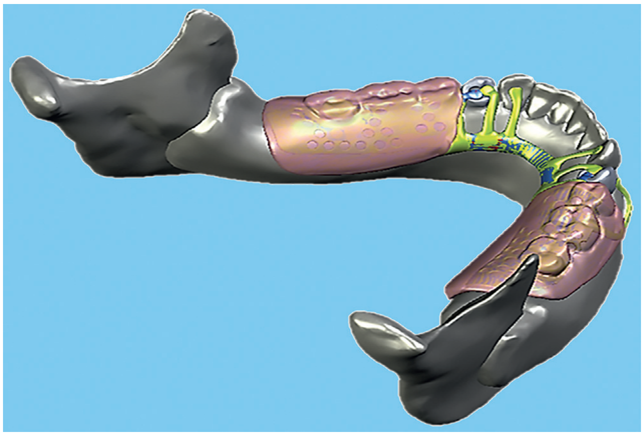

Figure 4. Multiple solid parts (implants, IARPD metal framework parts, IARPD acrylic resin structures, and attachments components) positioned as one entity in relation to mandibular model (exported as Parasolid XT file). IARPD, implant-assisted removable partial denture.

occlusal rest direct retainer situation, the metal framework had a stress distribution where the stressed region extended up to the end of the finishing line, the junction between the metal framework and the acrylic resin denture base.

The principal stress distribution in the distal occlusal rest direct retainer situation showed that the maximum principal stress occurred on the fitting surface of the proximal plates and indirect retainers and that the minimum principal stress occurred on the upper side of the occlusal rest direct retainer and indirect retainers (Fig. 7B). A similar principal stress distribution was observed in the mesial occlusal rest direct retainer. Such stress variation and resultant gradient could cause high deformation and potential failure of the retainer. However, the high-stress region extended in the upper surface of the denture base metal framework up to the junction between the metal framework and the acrylic resin denture base (Fig. 7A).

The maximum total displacements were 507 μm for the mesial occlusal rest direct retainer and 306 μm for the distal occlusal rest direct retainer. This demonstrates that the distal occlusal rest direct retainer was much stiffer and underwent approximately 66% less deformation than the mesial design. The deformation pattern in the metal framework structure highlights the fact that the maximum deformation occurred on the infrabulge retainers (I-bars) in both the mesial and the distal occlusal rest direct retainer designs (Fig. 8).

The maximum von Mises stress on the acrylic resin surface was 17 MPa for the mesial occlusal rest direct retainer and occurred on the lingual side of the prosthesis near the finishing line, and from this region, the stress pattern extended to the lingual surface up to the mesiobuccal surface of the second molar (Fig. 9A). A maximum von Mises stress of 29 MPa for the distal occlusal rest direct retainer was observed in the mesiolingual surface of the second premolar. This stress pattern further extended up to the distal occlusal surface of the second premolar (Fig. 9B). Hence the distal occlusal rest direct retainer design had a higher stress (approximately 72% greater) than the mesial occlusal rest.

The total displacement was found to be 130 μm for the mesial occlusal rest direct retainer design and was much larger (276 μm) for the distal occlusal rest direct retainer design (Fig. 10). The total deformation pattern in the IARPD structure highlights the fact that the maximum deformation occurred on the mesial area of the denture base and infrabulge retainers (I-bars) in both matrix designs. Also, the rotational effect improved on the distobuccal surface of the distal occlusal rest direct retainer design, and buccal flange rotational effects were not noticed (Fig. 10B).

The deformation pattern of the abutment teeth, bone, and soft tissue (Fig. 11) was subsequently analyzed. Maximum deformation was found in the abutment teeth

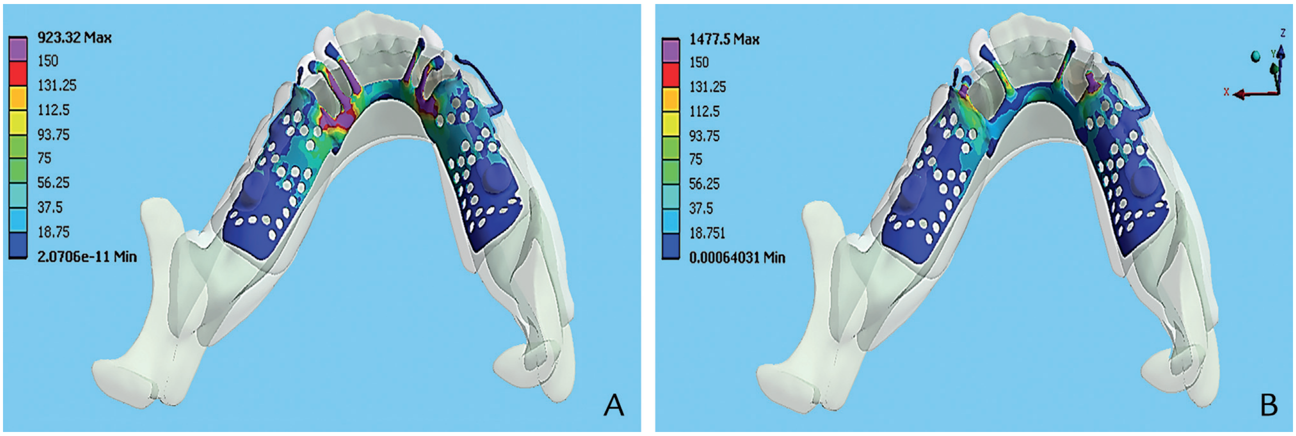

Figure 5. von Mises stress distribution showing maximum stress on metal framework of prosthesis (MPa). A, Mesial occlusal rest. B, Distal occlusal rest.

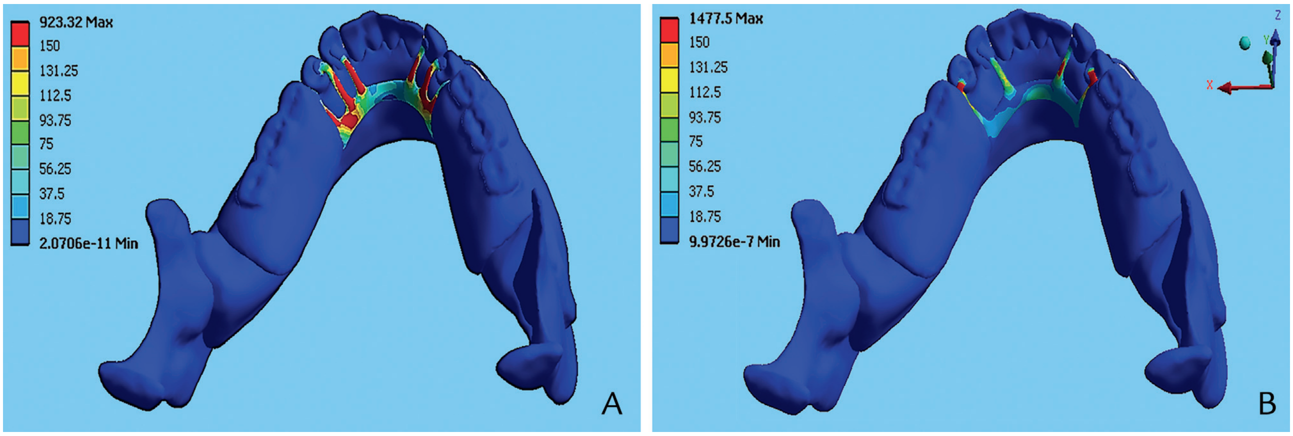

Figure 6. High-stress regions at junction between metal framework and acrylic resin structure of prosthesis (MPa). A, Mesial occlusal rest. B, Distal occlusal rest.

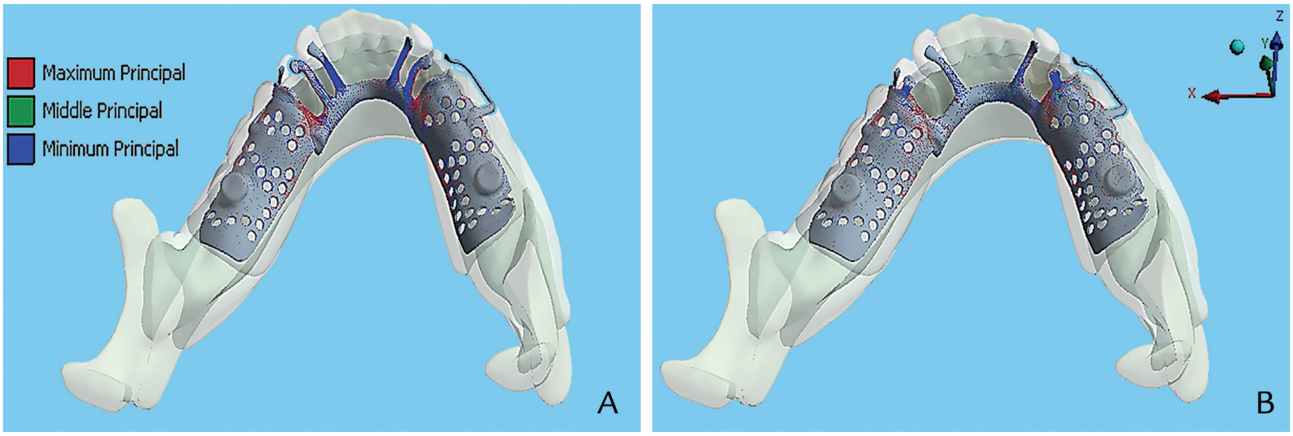

Figure 7. Tensile stresses (red) and compressive stresses (blue) on upper side of direct retainers. A, Mesial occlusal rest. B, Distal occlusal rest.

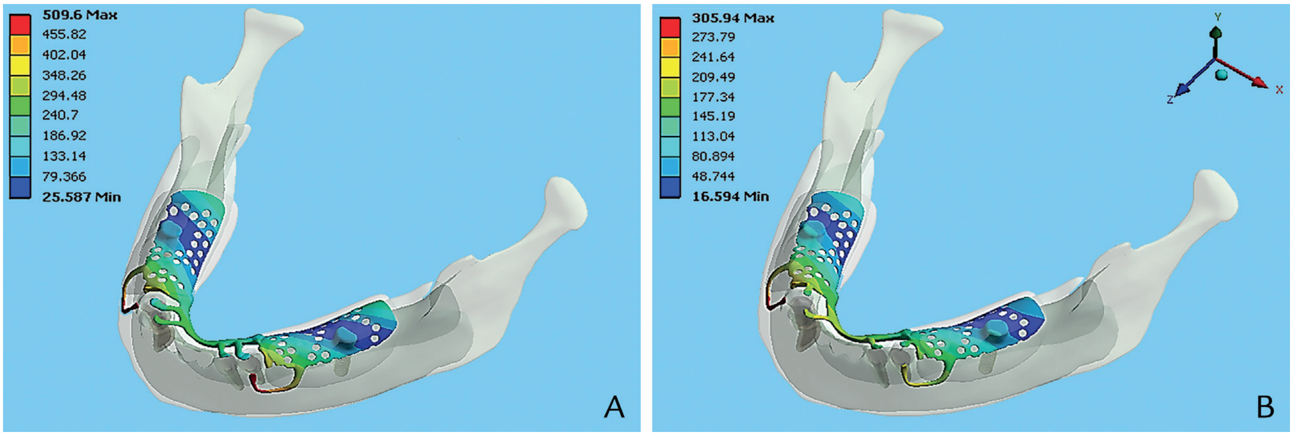

Figure 8. Deformation (total displacement) of metal framework surface of prosthesis showing maximum displacement locations (μm). A, Modified denture base metal framework of mesial occlusal rest. B, Modified denture base metal framework of distal occlusal rest.

on the mesial occlusal rest direct retainer (Fig. 11A). The maximum deformation occurred in all anterior teeth and the symphysis region of the mandible for the distal occlusal rest direct retainer (Fig. 11B). The values of the maximum total displacements were 220 μm for the mesial occlusal rest direct retainer and 182 μm for the distal occlusal rest direct retainer designs. A summary of the results with the maximum stress and displacement

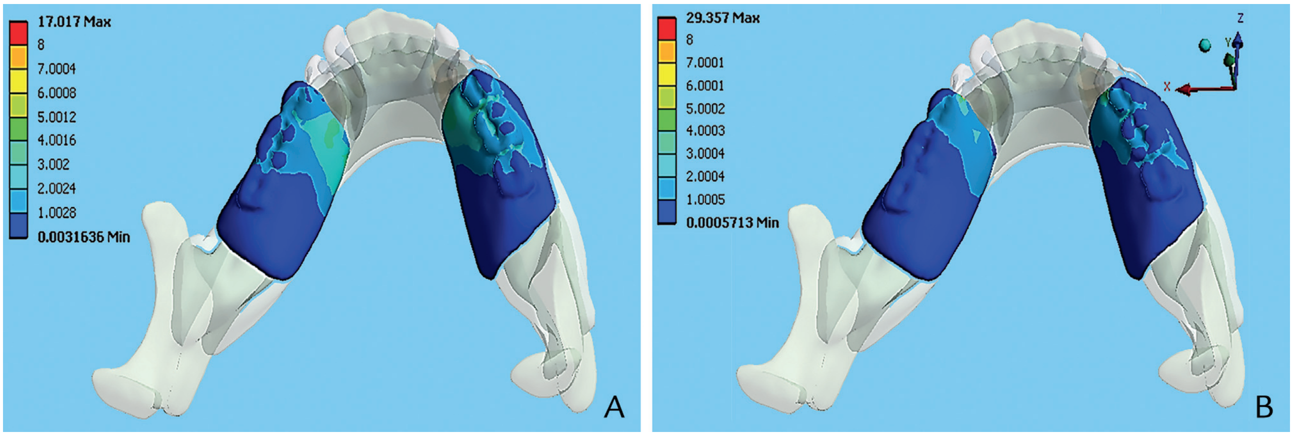

Figure 9. Stress distributions showing maximum von Mises stress on acrylic resin surface of prosthesis (MPa). A, IARPD with mesial occlusal rest. B, IARPD with distal occlusal rest. IARPD, implant-assisted removable partial denture.

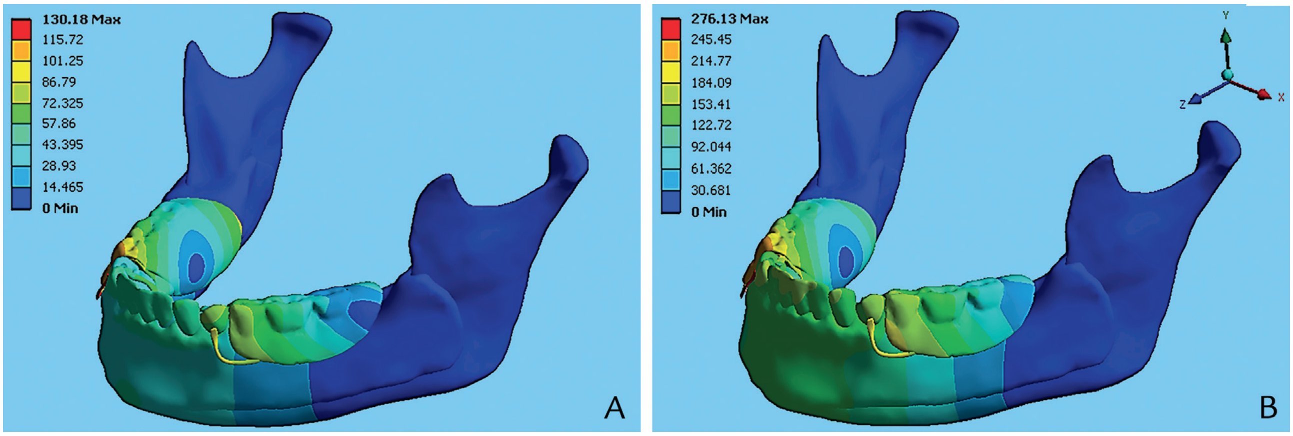

Figure 10. Total deformation showing maximum displacement locations (µm). A, Modified denture base metal framework of mesial occlusal rest direct retainer model. B, Modified denture base metal framework of distal occlusal rest direct retainer model.

values is presented in Table 2, which also includes the maximum values of the displacement of all components.

DISCUSSION

Mandibular Kennedy class I RPDs exhibit complex biomechanical behavior because of the supporting structures of the teeth and mucosa, each with different properties.[18]An osseointegrated implant has been suggested as a means to provide additional support and retention, which would reduce biomechanical complexities.[12] It is expected that an implant incorporated into a mandibular Kennedy class I RPD would reduce the rotational movement of the prosthesis.[19] However, no significant change of movement between the RPD and IARPD was identified in this study.[20] Changing the position of the occlusal rest direct retainer from the mesial side of the abutment teeth to the distal side did reduce stress in the IARPD structure,[10] although the rotational movement still existed. A combination of a mismatch of deformation between the mesial and distal areas of the denture base and the movement of the abutment teeth leads to the rotational behavior of the denture base of IARPDs.

Connecting an acrylic resin base to both the metal framework and the rigidly fixed implant often contributes to the rotational displacement of the prosthesis during loading. This study was conducted to analyze the effect of connecting the denture base metal framework to the implant with the aim of decreasing the rotational movement of the IARPD. The analysis revealed a significant increase in stress on the distal occlusal rest direct retainer metal framework structure, where the denture base metal framework is connected to the implant (Fig. 5B). In addition, the high-stress region remained primarily around the distal occlusal rest; with the mesial occlusal rest, the stressed regions extended up to the lingual bar and the denture base metal framework, exceeding the finishing line. This made the acrylic resin structure prone to failure by cracking. This

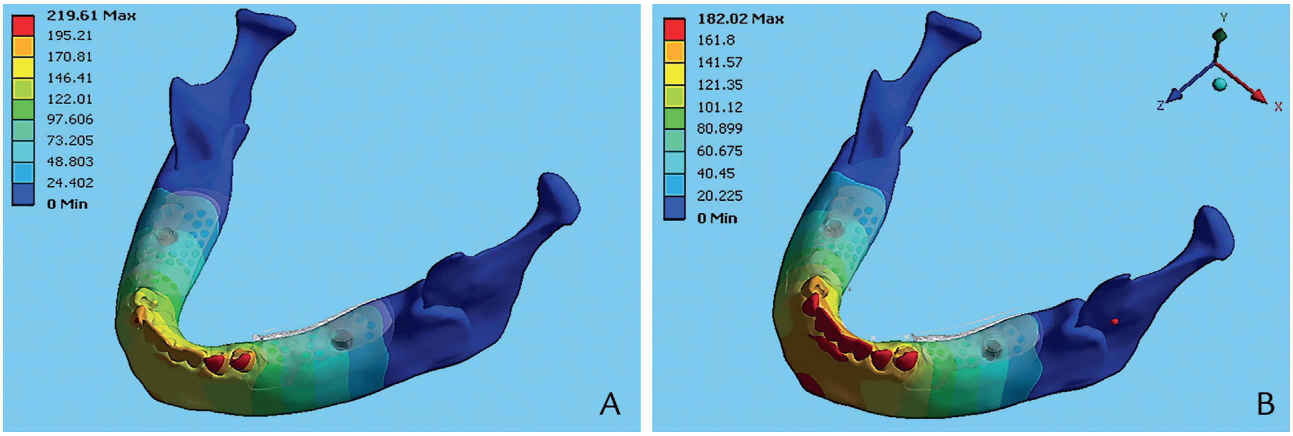

Figure 11. Deformation (displacement) pattern of prosthesis underlying tissue (μm). A, Modified denture base metal framework of mesial occlusal rest. B, Modified denture base metal framework of distal occlusal rest.

Table 2. Stress and displacement values for metal and acrylic resin structures

	Maximum von Mises Stress (MPa)		Maximum Framework Displacement (μm)		
Design	**Metal**	**Acrylic Resin**	**Metal**	**Maximum Total Displacement (μm)**	**Maximum Abutment Tooth Displacement (μm)**
Mesial	923	17	507	130	220
Distal	1478	29	306	276	182

Table data summarize stress and displacement values for metal and acrylic resin structures of implant-assisted removable partial denture with modified meshwork.

was more noticeable when tensile stresses were generated on the upper surface of the denture base metal framework of the IARPD (Fig. 7A). The maximum deformation of the metal framework occurred in the I-bar. The deflection of the I-bar tip was found to exert load and hence generate stresses in the surrounding material. For this reason, specific attention is required during the fabrication of a metal framework in terms of the taper and the radius of curvature ratio between the vertical and horizontal sections in order to reduce fatigue in the clasp arm.[21,22]

The acrylic resin structure showed an increase in maximum stress in the distal occlusal rest direct retainer design. The maximum stress was well beyond the flexural strength of 75 MPa of the acrylic resin material (Vertex Dental. http://www.vertex-dental.com/castapressCrystalClear). Although the maximum stress was higher for the distal occlusal rest direct retainer design, this stress remained on the surface of the premolar teeth and did not extend to the buccal flange of the acrylic resin structure. In contrast, the mesial occlusal rest direct retainer design had the maximum stress on the lingual side of the prosthesis near the finishing line, and, from this region, the stressed areas extended to the lingual surface up to the mesiobuccal surface of the second molar. The distal occlusal rest direct retainer with the modified denture base metal framework appeared to provide better support to the acrylic resin structure by reducing the stress on the surface of the acrylic resin base.

A reduced rotation effect in the distal position of the occlusal rest direct retainer was observed (Fig. 10B). The rotation effect in the distobuccal area was not perceived on the IARPD with the distal occlusal rest and was only found in the distolingual region. An increase in the maximum total deformation in the distal occlusal rest direct retainer along with a reduced rotational movement can explain why there was more vertical rather than lateral displacement. However, the mesial occlusal rest direct retainer underwent less deformation. The alteration of the denture base metal framework did not reduce rotational movements in the mesial occlusal rest direct retainer design.

The maximum displacement was observed on the underlying structure of the distal occlusal rest direct retainer and was greater than that on the mesial occlusal rest direct retainer. Large deformations occurred in all of the mandibular anterior teeth and extended to the symphysis region of the mandible in the modified denture base metal framework of the IARPD with a distal occlusal rest. This may indicate resistance to the lateral transverse bending ("wishboning").[23] Wishboning of the mandible occurs in the thinnest area, providing sites for stress concentration. This was manifested in the mesial of the canine, symmetrically through the mental fossae (anterior buccal depression) in the buccal aspect of the mandible, which is highlighted in Figure 12A (in cream color). On the lingual side, the uniform surface transition prevented deformity (Fig. 12B). If wishboning happens, deposition on the lingual side of the anterior mandible

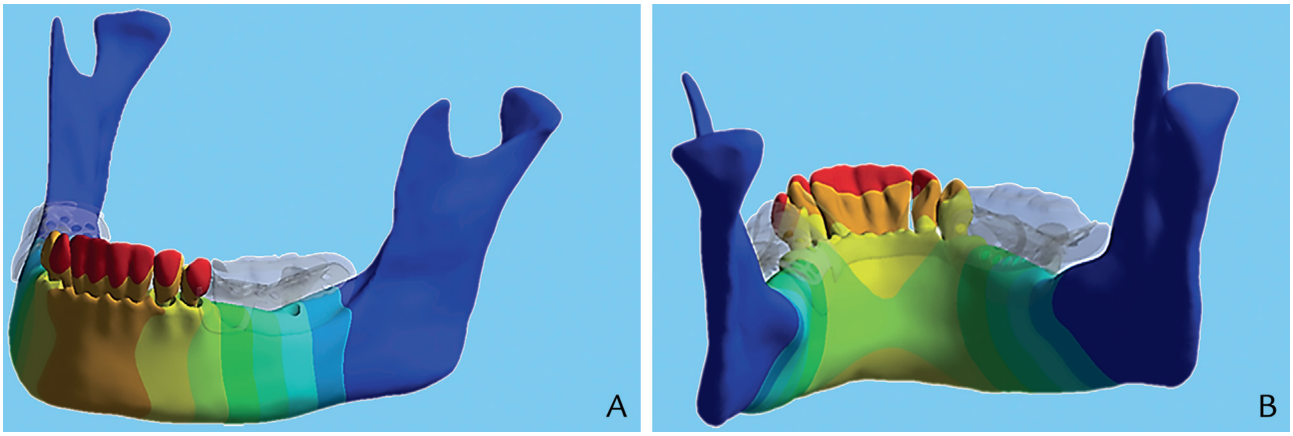

Figure 12. Wishboning highlighted with soft tissue removed. A, Buccal aspect. B, Lingual aspect.

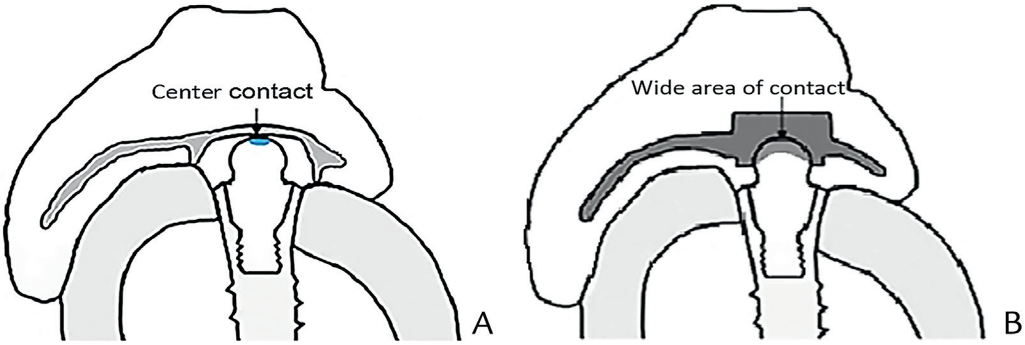

Figure 13. Implant-assisted removable partial denture contact surface between attachment and framework. A, Center contact. B Wide contact.

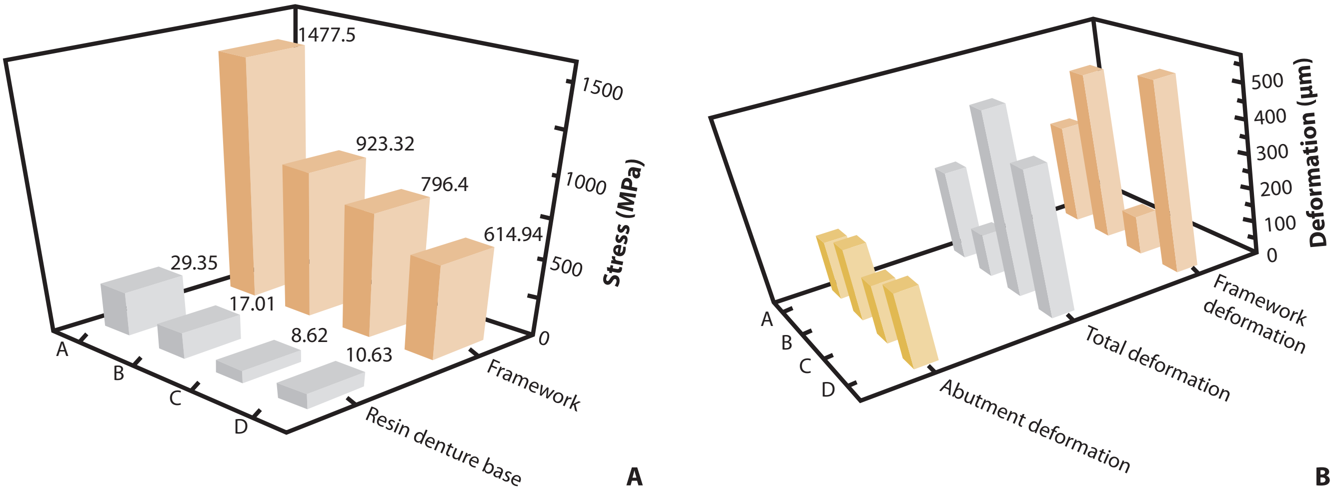

Figure 14. Comparison of maximum values of stress and deformation in implant-assisted removable partial dentures with different metal framework designs. A, Von Mises stresses values of metal framework and resin denture base. B, Displacement values of total, metal framework and abutment tooth. *All resin denture base stress values were multiplied by 10 for clear visualization.

and resorption on the buccal side would be expected. A bone microstrain exceeding 1500 μ causes bone deposition, and a microstrain below 100 μ results in bone resorption.[23] However, this study identified a microstrain range between 140 and 180 μ in the symphysis region. Further study is required to investigate the response of mandibular bone during the loading of an IARPD with a distal occlusal rest.

Lower deformation was found to occur on abutment teeth with the distal occlusal rest direct retainer design than that with the mesial occlusal rest direct retainer design. The abutment teeth displacement occurs through the PDL. The PDL is assumed to be made of a homogenous material in most FEA studies[24,25] The homogenous material assumption of the PDL in an FEA might make the structural analysis less accurate.[26] However, the results of the present study are in accord with the findings of the nonhomogeneous PDL of FE studies, such as those by Rocha et al[27] and Archangleo et al,[18] showing that stress on the abutment teeth remains high with an IARPD, regardless of its homogenous or nonhomogeneous nature.

Brudvik[1] stated that where clinicians choose to make a custom metal casting framework over the ball attachment, the center of the ball surface only needs to be contacted (Fig. 13A). The reasoning behind this design was not explained. One possible explanation could be that a larger portion of the hemisphere of the ball component interacts with the matrix for the wide contact, thus leading to relatively higher wear (Fig. 13B). In addition, a close contact with little or no clearance between the ball and the matrix can lead to edge loading (Fig. 13B). Close contact of the ball and the matrix results in a greater surface matrix articular arc angle. However, the force is not exerted from the ball component; rather it is exerted onto the ball attachment. Therefore, small center contact can transfer nonaxial forces to the implant. Further study is needed to investigate the effect of contact surfaces on force transfer to an implant and underlying tissues.

The use of a resilient attachment in conjunction with an implant limits the movement of an IARPD in the sagittal plane, regardless of the matrix design.[10] The rotational movement of the prosthesis toward tissue needs to be limited in order to protect the abutment teeth from undesirable torques and forces.[2] Occlusal rest seats that direct occlusal forces along the long axis of the supporting teeth can provide resistance to movement toward tissue.[2] Distal positioning of an occlusal rest of an IARPD significantly decreased the displacement of the abutment teeth and the metal framework.[9] This is an important improvement, because it helps distribute the forces exerted on the components of the prosthesis (metal framework and acrylic resin) and distribution of forces more uniformly than with a mesial occlusal rest design (Fig. 14A). Although the total displacement of the denture base of the modified framework with distal occlusal rest remained relatively high (Fig. 14B), this could be attributed to a higher degree of resiliency that allows the prosthesis to distribute forces more favorably.

CONCLUSIONS

Within the limitation of the current study, the following conclusions were drawn:

1. Modifying the denture base metal framework with infrabulge retainers (I-bars) and the distal position of the occlusal rest of abutment teeth make the structure much stiffer; it undergoes approximately 66% less deformation than with the mesial design.
2. The metal framework provides support more effectively to the acrylic resin structure in the modified denture base metal framework with a distal occlusal rest direct retainer design than that provided by the mesial occlusal rest direct retainer design.
3. Moving the position of the occlusal rest from the mesial to distal side of the abutment tooth and modifying the denture base metal framework reduced the displacement of the metal framework and abutment teeth.

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Noteworthy Abstracts of the Current Literature

Chairside CAD/CAM materials. Part 2: Flexural strength testing

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Objective. Strength is one of the preferred parameters used in dentistry for determining clinical indication of dental restoratives. However, small dimensions of CAD/CAM blocks limit reliable measurements with standardized uniaxial bending tests. The objective of this study was to introduce the ball-on-three-ball (B3B) biaxial strength test for dental for small CAD/CAM block in the context of the size effect on strength predicted by the Weibull theory.

Methods. Eight representative chairside CAD/CAM materials ranging from polycrystalline zirconia (e.max ZirCAD, Ivoclar-Vivadent), reinforced glasses (Vitablocs Mark II, VITA; Empress CAD, Ivoclar-Vivadent) and glass-ceramics (e.max CAD, Ivoclar-Vivadent; Suprinity, VITA; Celtra Duo, Dentsply) to hybrid materials (Enamic, VITA; Lava Ultimate, 3M ESPE) have been selected. Specimens were prepared with highly polished surfaces in rectangular plate (12×12×1.2mm3) or round disc (Ø=12mm, thickness=1.2mm) geometries. Specimens were tested using the B3B assembly and the biaxial strength was determined using calculations derived from finite element analyses of the respective stress fields. Size effects on strength were determined based on results from 4-point-bending specimens.

Results. A good agreement was found between the biaxial strength results for the different geometries (plates vs. discs) using the B3B test. Strength values ranged from 110.9MPa (Vitablocs Mark II) to 1303.21MPa (e.max ZirCAD). The strength dependency on specimen size was demonstrated through the calculated effective volume/surface.

Significance. The B3B test has shown to be a reliable and simple method for determining the biaxial strength restorative materials supplied as small CAD/CAM blocks. A flexible solution was made available for the B3B test in the rectangular plate geometry.

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