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RESEARCH AND EDUCATION

A 3D finite element analysis of glass fiber reinforcement designs on the stress of an implant-supported overdenture

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ABSTRACT

Statement of problem. Evidence regarding the effect of different glass fiber reinforcement designs on the biomechanical behavior of implant-supported overdentures is lacking.

Purpose. The purpose of this finite element analysis was to analyze the stress distribution in an implant-supported overdenture reinforced with a cast metal reinforcement bar and 4 different designs of unidirectional glass fiber to minimize the risk of denture base fracture.

Material and methods. A 3D edentulous mandible incorporating an implant-supported overdenture model without reinforcement (control, CT) or reinforced with 1 cast metal bar reinforcement (CM) was placed over the top of the implants and 4 unidirectional glass fiber reinforcements. The glass fiber bundle was placed over the top of the implants (GF), or 2 bundled halves were placed over the top (GO) of, between (GB), or distal (GD) to implants. Three patterns of occlusal loading were simulated: L1, all artificial teeth loaded in the long axis; L2, all left-side teeth loaded in the long axis; and L3, posterior left-side teeth loaded obliquely (45 degrees).

Results. Under L1 and L3, the tensile stresses were higher for CT, GD, and GO and lower for GF and CM. Under L2, no differences were seen between groups. Stresses were concentrated on the periphery of the O-ring connector, on the basal area, and on the middle-lingual region of the overdenture.

Conclusions. Reinforcements placed in the middle region and over the top of the implants provided better load distribution. Unidirectional glass fiber behaved as cast metal when used to reinforce the implant-supported overdenture. (J Prosthet Dent 2019;121:865.e1-e7)

An overdenture is a dental prosthesis that covers and is partially supported by natural teeth, natural tooth roots, and/or dental implants.[1] Implant-supported overdentures exhibit a mucosal supporting pattern similar to that of conventional dentures, and their retention and stability can be improved by the presence of implants.[2]

The fracture of a conventional denture base is a common finding[3] and is mainly caused by flexural fatigue and impact.[4,5] The midline region at the buccal frenum of the denture is the most common place for failures.[6] Fatigue of acrylic resin denture bases results from continuous exposure to chemical agents and cyclic mastication loads, which cause hydrolysis[7] and microcracks in stress-concentrated areas of the matrix polymer.[8-10]

Eventually, these cracks coalesce to form larger fissures, which leads to the failure of the polymer.[10] Impact failures usually occur as a result of accidentally dropping the denture during cleaning, coughing, or sneezing.[4,6] The fracture rate of overdentures ranges from 9.3% to 21.4% for 1- and 2-implant–supported overdentures (ISOs).[11]

Previous studies with a tooth-supported overdenture model found the greatest stress over the top of each coping.[12-14] Therefore, fractures of overdenture resin bases occur most frequently in areas adjacent to the abutment teeth.[15] This finding is observed in ISOs[11,16] and can be explained by the coping inside the denture

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Clinical Implications

Reinforcements of mandibular implant-supported overdentures must be placed over the implants extending to the anterior region. Bundled unidirectional glass fiber is comparable to traditional cast metal for reinforcing a mandibular implant-supported overdenture.

base becoming the fulcrum of movement.[17,18] The coping occupies a prosthetic space inside the denture base, making the acrylic resin base thin and susceptible to deformation or fracture.[15,16,19]

The inclusion of metal reinforcements in the acrylic resin base has been proposed to strengthen tooth-supported, 1- and 2-implant–supported overdentures.[17,19-21] Although they provide rigidity to the base, metal reinforcements have poor adhesion to the acrylic resin, which may outweigh the benefits of reinforcement.[5,22,23]

The fibers of synthetic materials, including ultrahigh-molecular-weight polyethylene (UHMWP), polyaramid, and E-glass, have been used to reinforce denture base resins.[24-27] The esthetic properties and the ability of these fibers to combine with the polymer matrix are fundamental for their success. UHMWP fibers adhere poorly to the polymer matrix even with plasma treatment.[28] Polyaramid fibers (Kevlar) are thermally and mechanically stable but are generally unesthetic.[29] Glass fibers provide good mechanical properties and can interrupt crack propagation.[10,14,30-34] Also, these fibers are esthetic and can be chemically bonded to the resin with silane coupling agents.[35]

The position and orientation of the reinforcement in a small construction such as a dental prosthesis influences mechanical properties.[36] Fiber reinforcement positioned in the center of a composite specimen with the fiber long axis perpendicular to an applied force will result in strong dental reinforcement.[37,38] Glass fiber reinforcements improve the mechanical behavior of overdentures when strategically placed over the abutments in ISO models.[37,39] However, the rhomboid specimens used in these studies are far from the complex ISO geometry that could address questions more closely related to the reinforcement of this type of prosthesis. Thus, varying the design of glass fiber reinforcement in an ISO structure is important and demands careful attention.

Three dimensional finite element analysis (FEA) provides remarkable information regarding stress distribution in systems with complex geometry and loading conditions, such as teeth or dental prostheses.[21] This analysis generates computational data that reveal the behavior of new materials or techniques under simulated clinical conditions. Therefore, the purpose of this study was to compare the effect of different designs of glass fiber reinforcement on the stress distribution of a 3D FEA of a mandibular ISO. A conventional cast metal reinforcement was included as a control. The null hypothesis was that the reinforcement design would not affect the stress distribution in the overdenture model.

MATERIAL AND METHODS

The proposal for this study was submitted for the Pontifical Catholic University of Paraná Institutional Review Board approval process (IRB #2-838-885). The virtual model of an edentulous jaw and an ISO were obtained from computed tomography, and a CAD model simulating reinforcement protocols was developed and analyzed with a 3D FEA. The mesh and boundary conditions were defined, and the stress behavior of the different designs of reinforcements was analyzed under 3 different loading protocols.

The geometry of an edentulous jaw was obtained from computed tomography (i-CAT; Xoran Technologies) carried out on the anterior-inferior region of a patient’s face through a total of 139 transversal slices, 0.4 mm apart. Similarly, a radiopaque duplicate of the patient’s overdenture was used to construct the virtual ISO model. These slices were saved in digital imaging and communications in medicine standard (DICOM) format and exported to a CAD modeling software program (ANSYS DesignModeler v11; ANSYS Inc).

The virtual models were edited (ANSYS DesignModeler v11) to include two 4.1-mm external hexagonal implants modeled perimetrically between the mental foramina, with 30 mm between the centers of each implant. The boundaries were defined, and the polymethylmethacrylate (PMMA) acrylic base, stock acrylic teeth, and ball and O-ring connectors were modeled (Fig. 1).

Six virtual models with variations in the presence, type, and position of a reinforcement bar were simulated for comparison. All designs were created from a master model, which exhibited a reinforcement bar (50×3×1.5 mm) that occupied the entire length of the crest region of the prosthesis between the O-ring connectors and the artificial teeth (Fig. 2). The virtual models and their different reinforcement designs are seen in Figure 3.

In the FEA model, the E-glass fiber content estimated to be inside the polymer matrix of polymethylmethacrylate (PMMA) was 2.3% volume percentage (vol.%) and 5.0 weight percentage (wt%). The volume fraction (V_f) was calculated in accordance with the following equation:[40]

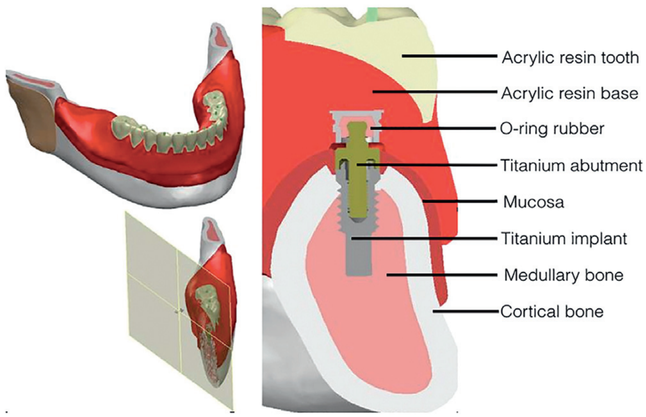

Figure 1. Cross-section view showing relationship between different structures.

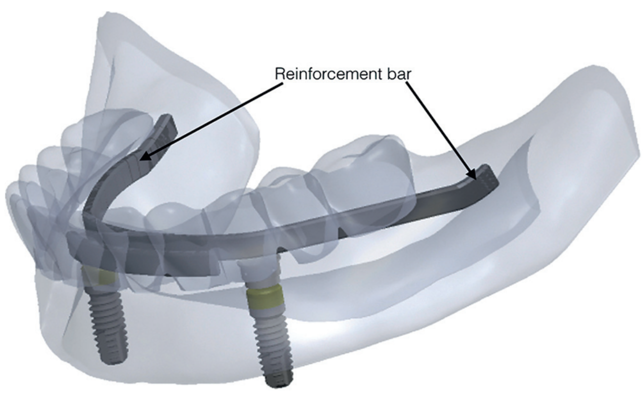

Figure 2. Profile of prosthesis with acrylic resin base, artificial teeth, and reinforcement bar.

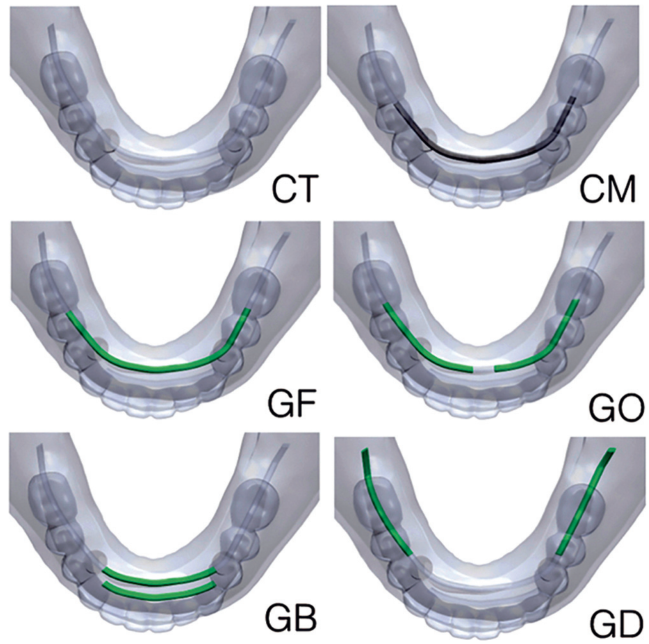

Figure 3. CT: Model without reinforcement (control); CM: Cast metal reinforcement bar (50×3×1.5 mm) placed onto connectors and extending 10 mm distal to center of each implant; GF: Whole bundled (50×3×1.5 mm) glass fiber reinforcement placed as described for CM; GO: Two bundled halves of glass fiber reinforcement over connectors; GB: Two bundled halves of glass fiber reinforcement placed between connectors; GD: Two bundled halves of glass fiber reinforcement, each placed distal to connectors without covering them.

$$V_f = \frac{\frac{W_f}{D_f}}{\frac{W_f}{D_f} + \frac{W_p}{D_p}} \times 100\%, \qquad (1)$$

where W_f is the estimated weight of the fiber (0.57 g), D_f is the density of the glass fiber (2.54 g/cm^3), W_p is the weight of the denture base resin (11.35 g), and D_p is the density of the denture base resin (1.19 g/cm^3). The concentration of fibers by weight was calculated according to the weight of the denture base resin and the weight of fibers incorporated.[9] The weight fraction of the fiber was estimated from its virtual volume (50×3.0×1.5 mm) and density, whereas the weight of denture base without the acrylic teeth was assessed from the patient mandibular overdenture used to construct the virtual ISO model.

The model was exported to a finite element simulation software program (ANSYS Workbench v11; ANSYS Inc). The corresponding Young modulus (E) and Poisson ratio (ν) of each element of the model were determined from the literature[21,41-43] (Tables 1 and 2). All materials were presumed homogeneous, linearly elastic, static, and isotropic, except for the E-glass fiber reinforcement. The mesh consisted of tetrahedral elements containing 10 nodes (solid 187). The average length of the elements in the prosthesis (including acrylic teeth, PMMA denture base, and reinforcement) and on the surface of mucosal contact was 0.75 mm. For the other parts, elements had an average length of 1.5 mm. With all components included, the final number of elements was 644 212 and that of mesh nodes was 359 265.

Three patterns of loading were applied to each model. An axial occlusal loading in all artificial teeth parallel to the long axis of the implants, with an intensity of 60 N for molars, 40 N for premolars, and 20 N for anterior teeth (L1), a 135-N axial occlusal loading on left-side posterior teeth parallel to the long axis of the implants (L2), and a 135-N oblique occlusal loading on left premolars and first molar at an angle of 45 degrees oblique to the long axis of the implants (L3).

RESULTS

Qualitative analysis consisted of the visual inspection of stress distribution areas for each group under each loading condition, and quantitative analysis consisted of stress peaks for these conditions. Only tensile stresses were analyzed due to the friable nature of the denture base resin

Table 1. Mechanical properties of isotropic materials

Material	Young Modulus (GPa)	Poisson Ratio
O-ring rubber	5	0.45
Cobalt-chromium cast metal	218	0.33
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.3
Acrylic resin teeth	2.94	0.3
Acrylic resin base	1.96	0.3
Titanium	110	0.35
Mucosa	0.68	0.45

Table 2. Mechanical properties of anisotropic unidirectional E-glass fiber material[44]

EL=Longitudinal elastic modulus (GPa)	39
Et=Transversal elastic modulus (GPa)	12
Glt=Longitudinal-transversal shear modulus (GPa)	14
Gtt=Transversal-transversal elastic modulus (GPa)	5.4
Vlt=Major longitudinal-transversal Poisson ratio	0.35
Vtt=Major transversal-transversal Poisson ratio	0.11

and because these stresses are usually responsible for the detachment or fracture of overdenture components.

Under L1, tensile stress distributions around the abutments and in the anterior basal area were higher for CT, GO, and GD, intermediate for GB, and lower for GF and CM (Fig. 4). CM and GF also exhibited the lowest stress peaks in the basal area (Table 3).

Under L2, the ISOs exhibited similar patterns of tensile stress peaks for all groups (Table 4). Stress areas were concentrated mainly at the periphery of the O-ring connector, at the labial flange, and in the basal area (Fig. 5).

Under L3, tensile stress distribution was concentrated in the anterior-lingual region. CT, GD, and GO showed the highest stress, whereas lower stresses were found in GF, CM, and GB (Fig. 6). The lowest stress peaks in this region were observed in GB, whereas GO exhibited the highest (Table 5).

DISCUSSION

This study assessed the effect of different designs of reinforcements on the stress distribution of 3D FEA of mandibular ISO virtual models. The null hypothesis was rejected because the reinforcement designs revealed different patterns of stress distribution. The cast metal and the whole bundle E-glass fiber reinforcements over the top of the implants exhibited better stress distribution than the other designs.

Synthetic fibers have been widely used to reinforce polymers in dentistry.[25-27] In the present study, glass fibers were chosen because they have been successfully used as denture base reinforcements due to their good esthetic and mechanical properties.[4,6,9,30]

The flexural fatigue of denture resin occurs after repeated flexing under function and is followed by the development, growth, and fusion of microscopic cracks. These larger fissures weaken the material and lead to the eventual failure of the structure.[10] The reinforcing effect of fibers is based on their ability to absorb stress from the polymer matrix and on the function of individual fibers as crack stoppers.[37-39] Although cast metal reinforcements can be used in implant overdentures, they are costly and time-consuming to fabricate.[16] Also, catastrophic failures in which a denture fractures into 2 pieces are more likely to occur with metal reinforcements, whereas fiber reinforcements arrest fracture lines and allow the denture to function until it can be repaired.[34]

The position of the reinforcement inside the resin affects its strength. Metal reinforcements placed perpendicular to the anticipated line of stress and fracture provide maximum strengthening.[5] For this reason, in the present study, both metal and glass reinforcements were placed perpendicular to the loading vectors simulated in L1, L2, and L3. This fact also supports the use of unidirectional glass fibers, whose anisotropic behavior provides high strength and stiffness in only 1 direction. Although woven fibers are isotropic, reinforcing the polymer in 2 directions, they are also effective in reinforcing implant-supported overdentures if placed only above or above and adjacent to the metal housing of stud attachments.[14]

According to the Krenchel factor, the efficiency of fiber reinforcement also depends on fiber content, with higher quantities of fiber increasing the flexural modulus and reducing the strain values of the FRC.[45] When compared with unreinforced PMMA, the fiber concentration (5 wt%) simulated in the FEA model of the present study is expected to increase the fracture load of PMMA up to 32%.[45] Although a higher fiber content (58 wt%) enhanced the transverse strength of PMMA to a higher percentage (146%),[9] it is difficult to increase the concentration of fibers in a polymer matrix to a level at which an adequate reinforcement effect is achieved. The major problem associated with increased fiber loading is the lateral spreading of fibers, which causes the inhomogeneous distribution of fibers in the matrix and the poor wetting of fibers.[9]

Adequate bonding between the fibers, polymer matrix, and coupling agent allows force transfer from polymer to fibers to achieve maximum reinforcement.[35] In the present study, the interface adhesion of the FRC or metal bar to the PMMA denture base was not characterized in the FEA model. The interface adhesion of the FRC or metal bar to the PMMA denture base is expected to be different in the actual situation. When the preimpregnation polymer of the fibers of the FRC is the same as that in the reinforced structure,[40,46] an adequate interfacial adhesion between the FRC and the reinforced material is expected. In contrast, Co-Cr metal

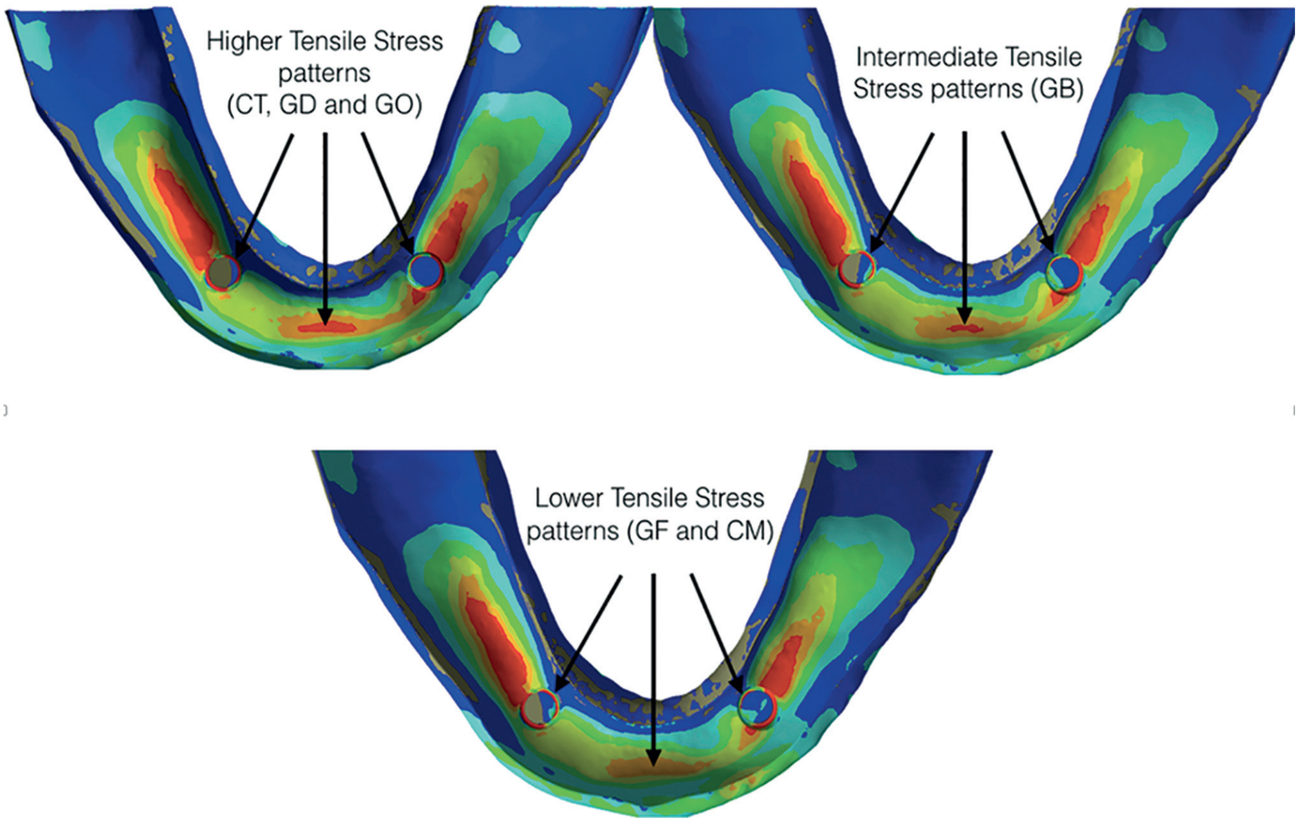

Figure 4. Tensile stress distribution in periphery of O-ring connector and basal area under L1. L1, all artificial teeth loaded in long axis.

reinforcements do not exhibit adequate adhesion to PMMA.[36]

In the present FEA study, the connection at the interface between the E-glass fiber and the PMMA matrix was defined as bonded, and the FRC was modeled as nonimpregnated fibers. This strategy allowed an analysis of the model from a macroscopic point of view, where the mechanical properties of the components and the geometry of the model play a greater role in the simulation than other properties such as the micrometric surface irregularities of the FRC and the bond strength connections with the polymer matrix.[47]

The abutment inside the denture base becomes the fulcrum of the overdenture movement.[17] Moreover, the acrylic base around the overdenture abutments becomes thinner and more susceptible to strain and fracture.[15,16,19] Reinforcements placed on the top of the attachments in implant-supported overdentures could prevent prosthesis deformation and fracture.[14,36] In the present study, the overdenture model exhibited better stress distribution and peaks when the reinforcement was not only placed on top of the attachment but also when it was undivided and located in the middle region between the 2 implants. The whole bundled group or the 2 bundled halves of glass fiber reinforcements placed in the anterior region were investigated because this region may be susceptible to deflection during mastication.[12,13,17] In general, the 2

Table 3. Tensile peaks (MPa) under axial occlusal loading in all teeth (L1)

Groups	Periphery of O-ring Connector	Posterior-Superior Region of Base	Basal Area	Base-Teeth Interface
CT	4.84	2.37	3.67	2.82
CM	4.73	2.36	3.52	2.62
GF	4.78	2.37	3.60	2.72
GO	4.79	2.37	3.64	2.71
GB	4.82	2.36	3.55	2.77
GD	4.80	2.40	3.68	2.81

minor peaks of tensile stress were observed in the cast metal reinforcement (CM), followed by the whole bundled piece of unidirectional glass fiber reinforcement over the implants (GF). The higher elastic modulus of the cast metal reinforcement contributed more to the reduction of the deflection and stress of the prosthesis than the bundled glass fiber.[22,23]

The loading applied during the simulations in the present study were close to the threshold value (100 N) for bone resorption.[19] Under L1, groups with 2 bundled halves of glass fiber (GO, GB, GD) were comparable to control (CT), with the highest stress concentration observed around the abutments and basal area. Under L3, the 2 bundled halves of glass fiber between the connectors (GB) generated the lowest tensile stress in the middle region (3.68 MPa), even smaller than the cast metal (CM). Similarly, although GO and GB

Table 4. Tensile peaks (MPa) under axial occlusal loading in all left-side teeth (L2)

Groups	Periphery of O-ring Connector	Labial Flange	Basal Area
CT	3.24	2.80	1.88
CM	3.21	2.65	1.90
GF	3.33	2.76	1.89
GO	3.35	2.76	1.90
GB	3.28	2.75	1.88
GD	3.24	2.79	1.86

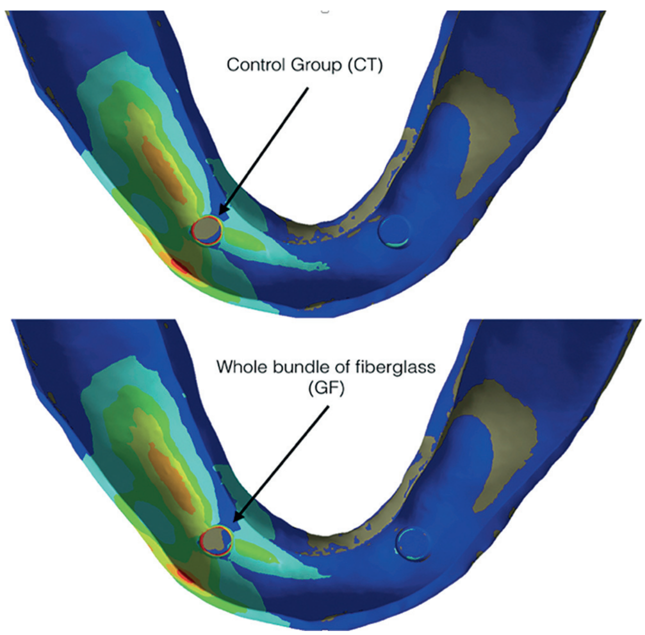

Figure 5. Similar tensile stress distribution in periphery of O-ring connector, labial flange, and basal area under L2. L2, all left-side teeth loaded in long axis.

decreased the tensile stress in regions with higher tension, they did not prevent the deflection of the prosthesis overall because they did not cover the entire area subject to deflection. The absence of reinforcement generated the greatest tensile stresses around the abutments (7.7 MPa), which may reduce the clinical survival of these components and raise prosthetic maintenance concerns.

Lower tensile peaks were observed under axial occlusal loading either in all teeth (L1) or in left teeth (L2) compared with the oblique occlusal loading in the left posteriors (L3). L1 was simulated because the best stress distribution is achieved by the bilateral loading of overdentures, supporting the recommendation that patients masticate on both sides simultaneously.[19] Oblique loading (L3) best simulates mastication excursive movements.[21] Under L3, the variations of the structural reinforcements and their roles in the dynamics of the prosthesis became clear. The anterior-lingual region of the prosthesis had the highest peaks of stress throughout the base in 5 of the 6 designs.

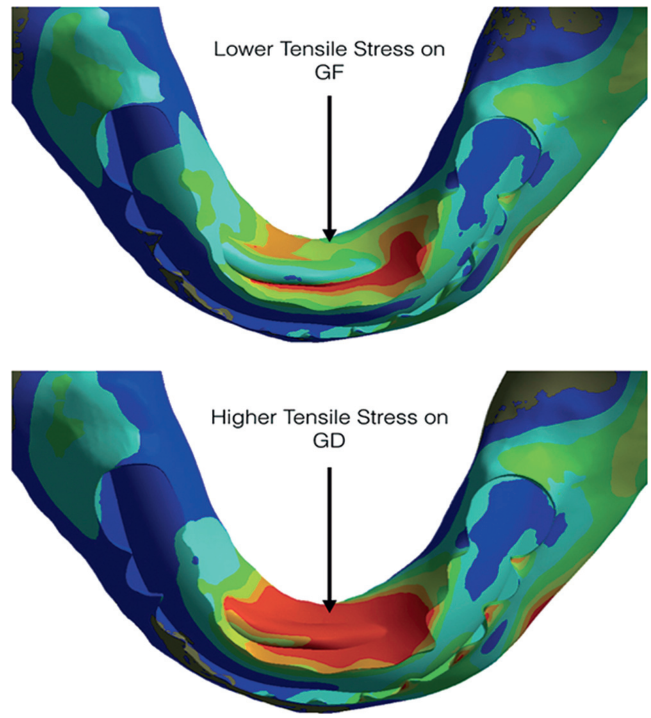

Figure 6. Tensile stress distribution in lingual region under L3. L3, posterior left-side teeth loaded obliquely at 45 degrees.

Table 5. Tensile peaks (MPa) under oblique occlusal loading in left-side posterior teeth (L3)

Groups	Periphery of O-ring Connector	Anterior-Lingual Region of the Base	Labial Flange
CT	3.87	4.95	3.57
CM	3.25	4.05	3.15
GF	3.95	4.26	3.33
GO	3.27	6.50	3.46
GB	7.70	3.68	3.29
GD	3.91	4.95	3.55

The present study suggests that reinforcements with cast metal or whole bundled glass fiber could prolong the life of 2-implant–supported overdentures. Although geometry variations of the overdenture base, bone, and mucosa may influence the stress and strain distribution, local spot stresses in the anterior region and around abutments are expected to have similar trends. A major limitation of this study is the extension of its qualitative results to an oral environment in which a complex biomechanical condition is present. Future clinical follow-up studies are needed.

CONCLUSIONS

Based on the findings of this finite element analysis study, the following conclusions were drawn:

1. Reinforcements placed in the middle region and over the top of the implants produced the best stress behavior.

2. Among the glass fiber reinforcements in the 2-implant–supported overdenture model, the whole bundled glass fiber design was comparable to the traditional cast metal design.

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