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Three-Dimensional Finite Element Analysis of Stress Distribution in Implant Supported Dentures: A Review

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Abstract: Stress distribution is a key factor that affects the success of implant prostheses. In the past 3 decades, 3-dimensional finite element analysis (3D FEA) has been used widely to predict stress distribution in implant denture systems and surrounding tissues. By understanding the application and limitations of 3D FEA, the clinician will be able to interpret the results of the studies on stress distribution and extrapolate these results to dental practice. This article reviews the current status of 3D FEA applications in implant supported denture studies and discusses findings from these studies in relation to implant supported dentures.
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1. Introduction

Since applied to dental implants in the early 1980s, 3-dimensional finite element analysis (3D FEA) has become an increasingly useful tool for predicting the effect of stress on implant supported dentures and surrounding tissues.[1-19] Masticatory Loads induce axial force and bending moments and produce stress gradients in implant denture systems, and the key factor for success or failure of implant prostheses is the way of loads transmission and stress distribution. Thus, the prediction of stress effects on implant supported dentures is considered necessary.

From the biomechanical viewpoint, there are 3 main classes of implant supported dentures, including implant supported fixed dentures, implant supported overdentures and combined natural tooth and implant supported dentures.[20] 3D FEA of stress distribution in implant denture systems is usually complicated, because dentures can be loaded not by a single load but by multiple loads and in varying directions.[16] This article reviews the current status of the application of 3D FEA to implant supported dentures and discusses findings from 3D FEA studies in relation to implant supported dentures.

2. Implant supported dentures

3D FEA can simulate the interaction phenomena between crowns (or bridges) and implants. Analysis of stress distribution is facilitated by the ability to investigate the various superstructure, loading, implant and surrounding tissue variables. Factors that influence load transfer from fixed prostheses to implants and surrounding bone and resultant stress distribution include designs of implant structure and superstructure, loading conditions, superstructure material properties and mandibular flexure.

Implant supported crowns

Different inclinations of abutments and fixures affect stress distribution at the bone-implant interface. Martini et al used 3D FEA models of implant supported central incisor crowns with straight and 15-degree abutments to analyze the effects of stress in bone. They concluded that the implants with straight abutments generated higher stress values in bone, and stress concentration was potentiated when the load was exerted obliquely.[21] In the posterior mandible, Lan et al investigated stress distribution in the splinted crowns supported by implants with three tilting types by 3D FEA. The research showed that the stress values were significantly increased when loads of different types were exert on the crowns supported by distal tilting implants. The authors suggested that placement of the implants with distal tilting should be avoided in the posterior mandible.[22] However, in another 3D FEA study, Cruz et al analyzed stress distribution in three splinted crowns supported by three titanium implants with various inclinations, and the result indicated that the presence of tilting implants in the posterior teeth area did not induce stress concentration in any point around the implants.[23]

With some previous findings, researchers held the opinion that large implant diameters provide for more favorable stress distribution.[24,25] In a recent study, 3D FEA was used to analyzed the relationship between implant diameter and peri-implant bone thickness, occlusal load direction, and stress levels in the first molar region. This 3D FEA results supported that only 6.0-mm implants were effective in reducing bone stress concentration and preserving bone height.[26]

With regard to platform switching, the theoretical analysis implied that the influence of platform switching was more evident for cortical bone than for trabecular bone, mainly for the external hexagon implants. The external hexagon implants showed less stress concentration in switching platforms comparing to the internal hexagon ones.[27]

Besides designs of implant structure, superstructure designs also influence stress distribution in implant supported crown and surrounding bone. Falcón-Antenucci et al used 3D FEA models to simulated a mandibular bone section with an implant and crown. The crown was simulated using three cusp inclinations: 10 degrees, 20 degrees and 30 degrees. The von Mises stress maps showed that with cusp inclination increasing, stresses on the implant and implant-abutment interface increased and stresses on the cortical bone decreased.[28] The conclusion above was similar to that of a later 2D FEA study.[29] In addition, Huang et al reported that induced stress in crestal bone was sensitive to the scheme of crowns splinting, and the benefit of loading sharing by splinted crowns was notable especially when implants in the premolar and molar regions had different supporting ability.[30]

Properties of various crown materials influence stress transfer from superstructure to implant abutment significantly.[31-33] Sevimay et al used a 3D FEA model of implant supported mandibular second premolar crowns with different materials to evaluate the amount and localization of stress. For a 300-N vertical force applied to the centric relation stop points of the crowns investigated, they found that porcelain fused to base metal and In-Ceram crown designs transferred less stress to abutments and induced higher von Mises stress values within the framework than porcelain fused to noble metal and IPS Empress-2 crown designs.[32] In a lately reported 3D FEA study, Gomes et al analyzed the effect of different crown materials on stress distribution in implant crowns. They concluded that the use of various materials to fabricate crowns did not affect stress distribution in supporting bone and that the retention screw received less stress when the design of porcelain fused to zirconia was used .[33]

Implant supported fixed bridges

Stress distribution in implant supported fixed bridges is more complex than that in implant supported crowns, because occlusal load at one point of the bridge causes varying stress distribution in all prosthesis components and surrounding tissues.[34,35] Researchers found ways to optimize the designs of implants and superstructures for more favorable stress distributions by 3D FEA method. Meric et al compared the effects of micro thread collar structure and non-micro thread collar structure of implants on stress distribution in the bone as well as in the fixure-abutment complex, in the framework and in the veneering material of 3-unit fixed bridges and cantilever fixed partial dentures. For 3-unit fixed bridges, micro thread collar structure was contributive to decrease the stress values in the cortical bone and the implant-abutment complex when the simulated chewing forces were applied to prostheses.[36] As for cantilever fixed partial dentures, higher stresses were located in the cortical bone and implant-abutment complex under the vertical load while decreased stresses in the cortical bone and implant-abutment complex were noted when horizontal and oblique loads were applied in the micro thread collar structured model.[37] Proper superstructure designs are also helpful to reduce unfavorable stress. Some 3D FEA studies demonstrated that reduction in superstructure height or the design of the conventional fixed bridge without distal cantilever produced better stress distribution and that existent of misfit between superstructure and implants and undesirable pontic designs increased stress magnitude in fixed prostheses and supporting bone.[38-42]

The elastic moduli of different superstructure materials had different effects on stress distribution in prosthesis frameworks, the implant-abutment complex and the implant-bone interface.[43-45] With 3D FEA method, Erkmen et al accessed stress effects of 3-unit prostheses composed of two types of superstructure materials in different loading conditions. When comparing porcelain fused to cobalt-chromium, the composite material with low elastic moduli produced higher stress values in the implant-abutment complex, but it could eliminate the excessive stresses in the implant-bone interface and maintain normal physiological loading of surrounding bone, therefore minimizing the risk of peri-implant bone loss.[43] In an early 3D FEA study, Stegaroiu et al also acquired the result that the highest increase in stress with less rigid resin prostheses was found in the implant-abutment complex under axial load. However, the protective role of low elastic moduli material for the implant-bone interface could not be demonstrated in the limitation of their investigation.[44]

Implant supported fixed complete dentures

Implant supported fixed complete denture is supported generally by four to six implants, and implants inclinations and cantilever lengths significantly influence stress distribution in superstructure framework and implant-bone interface under various loading conditions.

A controversial problem exists as to the advisability of the design of posterior implants tilting distally. In some articles, 3D FEA models of mandible or maxilla with distal implants tilted showed that in different loading conditions higher stress concentrations were detected in the peri-implant bone, compared to the models with parallel implants.[46-48] However, via 3D FEA, Bevilacqua et al and Fazi et al found that the presence of distal implants tilted by 15 to 45 degrees decreased the amount of stress generated in the peri-implant bone and frameworks and resulted in a more favorable stress distribution . They commended the design of posterior implants tilting distally to clinical rehabilitation of edentulous situations.[49-51]

Furthermore, loads on cantilever sections of fixed full dentures could result in stress concentration at the implant-bone interface, especially in the cortical bone around the neck of implants, and with reduction of cantilever length stress values decreased significantly.[47,49,50,52]

A previous study believed that the use of low elastic moduli material for superstructure predicted larger stresses at the bone-implant interface on the loading side than the use of rigid material for superstructure with the same geometry.[53] Sertgoz used 3D FEA to investigate the effects of three different occlusal surface materials (resin, resin composite, and porcelain) and four different framework materials (gold, silver-palladium, cobalt-chromium, titanium alloys) on stress distribution in six-implant supported mandibular fixed prostheses and surrounding bone. The results obtained demonstrated that using the superstructure material with a lower elastic modulus concentrated stress in the retaining screws of the prosthesis and thus increased the potential risk of prosthesis failure, but did not lead to substantial differences in stress patterns nor in values at the cortical and spongy bones surrounding the implants. In the analysis of his study, the optimal combination of materials was found to be cobalt-chromium for the framework and porcelain for the occlusal surface.[54]

In addition, mandibular flexure under functional loads may affect stress distribution in the bone around implants. Stress around the implant can be caused not only by local deformation of the bone, but also by the complex deformation patterns of the mandible.[20] In a series of studies, Naini and Nokar created 1-piece, 2-piece and 3-piece mandibular superstructures supported by six implants to investigate the effects of superstructure designs on stress distribution in the peri-implant bone during mandibular flexure. They found that 1-piece superstructure restricted mandibular deformation to almost half of the amount of the other two designs. Even so, a significant amount of stress at the cortical bone surrounding the implants was induced. The authors suggested that mandibular flexure was an important factor for stress distribution and it should be considered in designing implant supported mandibular fixed full dentures.[55,56]

3. Implant supported overdentures

The use of implant supported overdentures is viewed as a cost-effective treatment modality, for stability of full denture can be enhanced by implant attachments, and occlusal loads on the denture can be shared by edentulous ridge mucosa. Factors that influence stress distribution in prosthesis systems and adjacent tissues include edentulous bone conditions and arch sizes, occlusion patterns, superstructure material properties, and loading directions.

de Almeida et al set up 4 3-dimensional finite element models of a completely edentulous mandibular arch with 4 interforaminal implants supporting a prefabricated bar system. The bone types varied from type 1 to type 4 (Atwood Classification). Three unilateral posterior loads (L) of 150 N were exerted on the prosthesis: L1, perpendicular to the prefabricated bar; L2, oblique (30 degrees) in the buccolingual direction; and L3, oblique (30 degrees) in the linguobuccal direction. The maximum principal stress was found in the cortical bone of bone types 3 and 4. The maximum principal strain was observed in type 4 cortical bone for all loads. Bone types 1 and 2 showed the lowest stress concentrations. The authors concluded that the bone type was one of factors that influence stress distribution in the bone supporting an implant overdenture anchored by a prefabricated bar.[57] In a later article, de Almeida et al used the same prosthetic method to restore edentulous mandibles of bone types 1 and 2 with different arch sizes(small, regular and large). The corresponding 3D FEA models were built. The results showed that tensile stress was more evident than compressive stress in types 1 and 2 bone. The large arch model had a higher influence on the maximum principal stress values than did the other formats, mainly for type 1 bone.[58]

Many researchers investigated the influence of occlusion patterns on stress distribution at the implant-bone interface. Vafaei et al used 3D FEA to assess stress distribution in models of edentulous mandibles with implant-retained bar-supported and ball-supported overdentures. Loads of 60N were exerted, respectively, on second molar mesial, first molar mesial, and first premolar in protrusive and laterotrusive motions. The authors found that strain was mostly detected in the apical of the fixtures and least in the cervical when bar design was used. On the nonworking side, however, strain was higher in the cervical and lower in the apical compared with the working side implant in protrusive motion. The strain values were closely similar in the two designs in laterotrusive motion. In terms of stress distribution, both designs were acceptable although a superior pattern was associated with the application of bar design in protrusive motion.[59] With the 3-dimensional finite element mandible models with six and four implants, Apicella et al investigated stress distribution induced by different occlusal schemes (canine guidance, posterior and anterior group functions). The results revealed that the posterior group function underwent a reduction in stress intensity in the cortical bone surrounding the implants (especially for the distal implant) compared with the anterior group function and canine guidance in both gnathologic reconstructions.[60] In a similar study, Yokoyama et al investigated stress distribution in edentulous mandibular bone supporting implant-retained 1-piece or multiple superstructures. They found that separating 1-piece superstructure into 2- to 4-piece superstructures increased the mechanical stress around supporting implants under the occlusal conditions of intercuspal contacts, canine-protected and group function occlusion. Canine load on the working side was distributed well in 1-piece and 3-piece superstructures. Based on the results of this 3-dimensional finite element model study, canine protected occlusion was recommended for 1-piece and 3-piece superstructures, and the unseparated superstructure was more effective in relieving stress concentration in the edentulous mandibular bone than the separated superstructures.[61]

Different occlusion patterns also affect stress distribution in the entire metallic framework and the cantilever region of implant-supported dentures. Greco et al modeled an edentulous mandible with the overdenture supported by 5 screw-shape, Brånemark dental implants located in the inter-mental foramen region and analyzed the effects of stress in a nickel-chromium framework with 12-mm bilateral cantilever covered by acrylic resin. The results displayed that the different occlusion patterns produced similar tension distributions in the cantilever region, and as the loads were dislocated distally, the tensions increased considerably. Regardless of the length of the cantilever, the highest tensions were always located in the region of the implant next to the load application point. In the range of the metallic framework, the canine guide generated greater tensions in the region of the first implant, while the bilateral balanced occlusion generated great tensions in the entire framework. The maximum tension found in the simulation of the bilateral balanced occlusion was 3.22 fold higher than the one found in the simulation of the disocclusion in canine guide. They concluded that the pattern of disocclusion in canine guide was ideal for implant-supported mandibular complete denture.[62,63]

Many clinicians are of the opinion that resilient(stress-breaking) attachments confer more favorable biomechanical characteristics compared with rigid ones. Two reported studies showed that as the elastic modulus of the stress-breaking attachments increased, the stress increased at the implant-bone interface. Resilient attachments allowed for an increase of the masticatory load transiting through denture bearing surface, and low levels of stress were maintained in the bone surrounding implants.[64,65] In a later investigation, Abreu et al evaluated the effects of different bar materials on stress distribution in an overdenture-retaining bar system and concluded that increasing the elastic modulus of the bar material led to the increase of stress in the bar framework, screw, and implant.[66]

The effect of load directions on stress distribution had also been investigated with 3D FEA. In their study, Luo et al found that the stress value of the cortical bone around abutments with 20-degree oblique force exerted on the overdenture was 2.2-3 times that with vertical force.[67] Some researchers also emphasized decreasing oblique biting force to reduce high stress peaks.[57,58]

4. Combined natural tooth and implant supported dentures

Combining natural teeth and implants to supporting fixed dentures has been the common treatment options for practitioners. However, controversy still exists as to the reasonableness of this design philosophy from a biomechanical perspective. There is a differential deflection between the viscoelastic intrusion of the natural tooth in its periodontal tissue and the minimal mobility of the osseointegrated implant. This difference may induce a fulcrum-like effect and resultant stress at the implant-bone interface.[2,68] Factors that influence stress distribution include denture span, implant diameter, connector type, framework rigidity, loading condition and number of splinted teeth.

With the use of 3D FEA, Naveau and Pierrisnard compared the mechanical behaviour of combined natural tooth and implant supported dentures with different superstructure spans and implant diameters. They found that stresses in the denture system with low superstructure span and high diameter implants were meaningfully less intense, and they recommended the use of wide-bodied implants in selected cases of short-span fixed partial dentures.[68]

Lin et al investigated the biomechanical interactions in tooth-implant supported fixed partial dentures under several loading conditions with different numbers of splinted teeth and connector types (rigid and non-rigid) by adopting 3D FEA. The result indicated that the loading condition was the main factor affecting stress developed in the implant, bone and superstructure of tooth-implant supported denture when comparing the type of connector and the number of splinted teeth. Minimizing the occlusal loading force on the pontic area by selective grinding procedures could reduce the stress values obviously. A non-rigid connector may more efficiently compensate for the dissimilar mobility between the implant and natural teeth under axial loading force but with the risk of increasing unfavorable stress in the superstructure.[69] Xie et al also investigated non-rigid connector in combined natural tooth and implant supported denture. They set up 3D FEA models to study stress distribution in bone tissues around the tooth and implant of the denture with the use of telescope retainer. The authors concluded that the stress surrounding the implant was declined significantly by the buffer of telescope retainer. when designing the fixed bridge supported by tooth-implant, telescope retainer on implant can be used to reduce the stress of bone tissues around the implant and to prevent damages to bone tissues.[70]

When investigating the influence of the rigidity of prosthetic materials on stress concentration in implant and surrounding bone, Dargahi et al used 3D FEA to assess stress distribution and deformation of the mandibular prosthesis supported by teeth and implants with the use of 3 different materials for implants and 4 different materials for framework. For the loading conditions used, it was found that the largest displacements occurred at the far ends of the framework and that the resulting deflection was highly dependent on the material properties of the framework. The modeling results revealed that more rigid frameworks led to a corresponding decreased stress in the retaining screws and that high-stress concentration areas moved from the neck of the implant towards the base of it, as the value of Young's modulus increased. Within the limitations of the study, the authors suggested that the first best prosthetic scheme was the Cr-Co alloy for the framework and the Ti alloy for the implant and the second best was the Cr-Co alloy for both the framework and the implant.[71]

By studying the relationship of stress distribution in the superstructure of fixed bridge supported by tooth-implant and various loading conditions, Wang et al found that stress distribution in abutments under oblique loads at 45 degrees was uneven and the peak value was 4-6 times higher than that under vertical loads. Stress concentration occurred with significant compressive stress. Compressive stress widely distributed in the middle area of occlusal surface of pontic, whose peak value under concentrated loads was significantly higher than that under disperse loads. The maximum displacement of implant abutment in medial-distal direction was greater than that of the neck of nature tooth. They advocated reducing oblique loads and concentrated ones as an effective solution for the mechanic complications of the superstructure.[72]

The number of splinted teeth affects the stress levels in the bone around the abutments. Dalkiz et al built up 3 free-end fixed osseointegrated prostheses models with various connection designs (i.e., rigidly connected to an implant and an abutment tooth, rigidly connected to an implant and two abutment teeth, and rigidly connected to an implant and three abutment teeth) by 3-dimensional finite element method. The stress values of three models loaded with vertical, buccolingual, and linguobuccal directions at 30 degrees angled to vertical axis forces were analyzed. Their FEA showed that when the fixed partial denture was connected to three natural abutment teeth and an implant, the lowest levels of stress in the bone were noted.[73]

5. Conclusion

3D FEA has been used extensively in the prediction of stress distribution in implant supported dentures. When applied to the implant prosthesis design, 3D FEA has suggested improved biomechanical performance when factors such as implant structure, occlusion pattern, prosthetic material properties, superstructure span length, loading condition, splinting scheme and attachment type are optimized.

This article reviewed the studies of 3D FEA in relation to implant supported dentures. 3D FEA is an effective computational tool to predict biomechanical performance of prosthesis systems. 3D FEA allows clinicians to know biomechanical features of prostheses well, and helps them to optimize prosthetic design.

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