ORIGINAL RESEARCH

Stress Generated in Bone with Different Configurations of Implants and Attachments in a Mandibular Implant-retained Overdenture: A Finite Element Analysis

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Abstract

Purpose: The purpose of this finite element analysis (FEA) study was to investigate stress distribution in bone distal to the implant by varying the attachments, implant configurations, and biomaterials in a mandibular implant-retained overdenture (IRO).

Materials and methods: Abutments were designed in four groups as per the geometry (ball and locator attachment) and biomaterial used for fabrication [grade IV titanium (Ti) and polyether ether ketone (PEEK)]. Eight finite element models were generated by varying either the attachment, material, and/or number of implants in each model. A force of 100 N was subjected to the implant assemblies of each model and von Mises stresses (VMS) and stress distribution patterns were evaluated and comparatively analyzed. In this *in vitro* study, the models were tested ($n = 8$) at axial (0°) angulation of force application.

Results: The maximum VMS of the order of 7.27 MPa were observed in the cortical shell of the distal bone in two implant models using locator attachments as opposed to 5.89 MPa observed in the three-implant model using ball attachments. High stresses were concentrated in one location in the implant-abutment connection area, especially in the models designed with PEEK locators that totaled 7.36 MPa, in both two-implant and three-implant configurations.

Conclusion: Finite element analysis (FEA) study confirmed that the three-implant configuration displayed a better stress profile when compared to two-implant specimens. Biomechanically, the most favorable combination was a three-implant configuration using PEEK ball attachments.

Keywords: Ball and socket attachments, Finite element analysis, Implant-retained overdenture, Locator attachments, Residual ridge resorption.

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Introduction

Edentulism reduces chewing efficiency, alters phonetics, and has a negative social impact on the patients' lives, making prompt rehabilitation an absolute necessity. Attainment of functional efficiency with conventional complete dentures (CCD) poses a challenge to clinicians when they are faced with highly resorbed mandibular ridges. The minimum standard of care for such patients is implant-retained overdenture (IRO) which is a functionally superior and economically feasible alternative.[1] The implants cause positive dynamic bone remodeling owing to the higher bite force generation of up to 300% as compared to CCD, and thus, restrict the disuse atrophy of bone. However, due to a lack of proprioceptive feedback, the patients are not able to regulate that bite force leading to high rates of bony resorption observed, especially in the posterior bony zones because of increased hydrostatic pressures on the mucosa.[2]

The amount of stresses under which the load-sharing determinants are exposed needs to be controlled for successful long-term use of the prosthesis. The forces applied to the implants depend on the magnitude, duration, type, direction, and magnification. The load transferred at the interface of bone and the implant also depends on the material properties of the implant and overlying prosthesis, implant geometry, implant surface structure, nature of the implant-bone interface, and quality and availability of bone.[3] To successfully manage the long-term ill effects of IRO, authors have attempted to alter the anchorage system employed for the retention of the prosthesis.[4] Studies[3,4] have compared the clinical success of ball attachments with that of locator attachments and found variable results with both attachments.

Experiments with splinted implants have also been conducted by varying the bar designs using a cantilevered ball or locator attachments.[5] Resilient liner attachments were compared with conventional plastic or nylon clip retaining elements in a study for splinted bar designs and analyzed the stress profile in the denture-bearing bone.[6] Researcher has also tried increasing the number of implants that support the mandibular overdenture to obtain a more favorable biomechanical profile of the implant system.[7] Comparison of bar and stud attachment systems has been done, but there has

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been no consensus over the superiority of one system over the other. The use of novel materials like PEEK has been advocated by some authors as a retaining element in place of conventional plastic or nylon retaining elements.[8]

According to the best of our knowledge, no research could be found that evaluated the efficiency of PEEK as the material for the fabrication of overdenture attachment abutments. The authors of this study attempted to exercise simplicity, efficiency, and cost-effectiveness by finding out the least complicated implant assembly design that displayed the most favorable force transfer characteristics, using a minimum number of implants and attachments made of PEEK material. Hence, in the current study, the geometry and biomaterial of the attachments were varied in conjunction with the use of two different implant placement configurations with the aim of obtaining biomechanically favorable clinical application of IRO.

The purpose of this FEA was to investigate stress distribution in bone distal to implants by varying the attachment, implant configurations, and biomaterial in a mandibular IRO. The null hypothesis was that varying the attachment design, material, and implant number had no influence on the stress distribution pattern in bone distal to the implant sites.

Materials and Methods

In the current FEA study, tapered internal hex bone level implants (diameter 3.2 mm and length 10 mm; SuperLine II, DentiumUSA) were used. The abutments were divided into four groups, grade IV Ti ball abutments, PEEK ball attachments (diameter 3.5 mm, collar height 1 mm; Implantium II, SuperLine, Dentium, United States of America), and grade IV Ti locator attachments and PEEK locator attachments (diameter 3.5 mm, collar height 1 mm; Implantium II, SuperLine, Dentium, United States of America). Two distinct placement configurations (two implants retained IRO with implants in regions A and E, and three implants retained IRO with implants in regions A, C, and E) were analyzed. For the FEA study, the implants and abutments of the four groups were modeled.[9]

A spiral computed tomography scan was used to record data obtained from the whole skull of an edentulous individual and was visualized and segmented using the Mimics 8.11 software. The mandibular data was extracted from the skull and exported as a stereolithographic file, which was converted to geometric models of the mandible using RapidForm 2004 software. The geometric model for each attachment group was also created at the same time but modeled separately using reverse engineering by measuring the dimensions of the physical parts with precision measuring tools. A mandibular denture was simultaneously scanned and subsequently converted into a geometric model. The files of the mandible, denture, and attachments were imported separately into Hypermesh 13.0 software and assembled at previously determined positions. The entire bone was set to a height of 12 mm and a thickness of 15 mm, including a 1.25 mm thick cortical bone with a D2-type pattern of trabecular bone and a 2 mm thick overlying mucosa.[3,4,10]

The geometric models with both attachment types (Figs 1 and 2) were generated and finally meshed into eight different finite element models based on the materials and loading:

- Design 01: An overdenture retained by two ball abutments made of grade IV Ti tested under the vertical loading of 100 N between the second premolar and first molar.
- Design 02: An overdenture retained by two ball abutments made of PEEK tested under the vertical loading of 100 N between the second premolar and first molar.

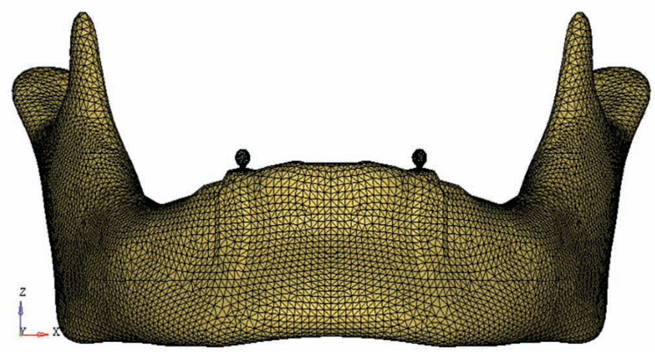


Fig. 1: Meshing of a three-dimensional geometric model of a human edentulous mandible with ball attachments

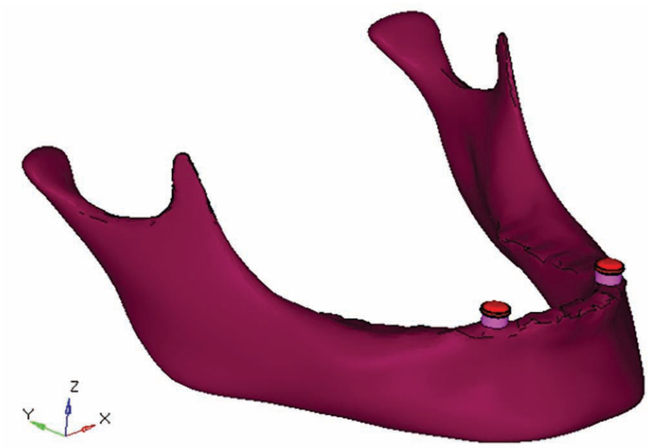


Fig. 2: Three-dimensional FEA model of the human edentulous mandible with locator attachments

- Design 03: An overdenture retained by two locator attachments made of grade IV Ti tested under the vertical loading of 100 N between the second premolar and first molar.
- Design 04: An overdenture retained by two locator attachments made of PEEK tested under a vertical loading of 100 N between the second premolar and first molar.
- Design 05: An overdenture retained by three ball attachments made of grade IV Ti tested under the vertical loading of 100 N between the second premolar and first molar.
- Design 06: An overdenture retained by three ball attachments made of PEEK tested under the vertical loading of 100 N between the second premolar and first molar.
- Design 07: An overdenture retained by three locator attachments made of grade IV Ti tested under the vertical loading of 100 N between the second premolar and first molar.
- Design 08: An overdenture retained by three ball attachments made of PEEK tested under the vertical loading of 100 N between the second premolar and first molar.

In the Hypermesh software, different material properties (Young's modulus and Poisson's ratio) were assigned to each component of the model [Implant (Ti6Al4V), 113.8 GPa, 0.342,[11] abutment (grade IV Ti)], 105 GPa, 0.34,[12] abutment PEEK, 3.7 GPa, 0.43,[13–15] cortical bone, 13.7 GPa, 0.3,[16] cancellous bone, 1.37 GPa, 0.3,[17] [poly(methyl methacrylate) (PMMA)], 2.1 GPa, 0.35.[18] All the materials were assumed homogenous, isotropic and linearly elastic, and assuming complete osseointegration, the interface between bone and implant was set to a bonded condition. The models were subjected to vertical forces of 100 N magnitude in the area between the second premolar and the first molar.[10] Subsequently, von Mises stresses (VMS) was measured for each component of the eight models, and stress distribution patterns were analyzed.

Results

The maximum VMS of the FEA results in each model (in MPa) are presented (Tables 1 and 2). In addition, the overall patterns of stress distribution in each group are shown (Figs 3 and 4). The high-stress areas were seen color-coded as red, and the low-stress areas were shaded blue. The intermediate stress zones were coded in green and yellow. A graphical representation of the VMS under axial loads with two attachments and three attachments to retain the overdenture was presented in Figures 5 and 6.

The lowest stress values were observed in the three-implant system using ball abutments as overdenture attachments, which were of the order of 5.89 MPa. Locator attachments in the two-implant configurations displayed a marginally less favorable stress distribution pattern, which totaled 7.27 MPa. In all the test specimens, the highest concentration of stresses was recorded in the neck region of the implant near the implant-abutment junction, which was color-coded as red.

The cancellous bone in the distal extension areas showed exponentially lower stress concentration, of the order of 0.53 MPa, as compared to 5.89 MPa recorded in the cortical bone. Keeping the target area of study in view, alteration in the biomaterials did not alter the stress profile in the bone appreciably, even though immense stress concentration was recorded in the implant with the use of PEEK attachments, more so with the use of PEEK locators, which was of the order of 7.36 MPa. Concurrently, PEEK attachments displayed the least stress concentration (0.39 MPa) and passed most of the stresses to the implant fixture below.

Discussion

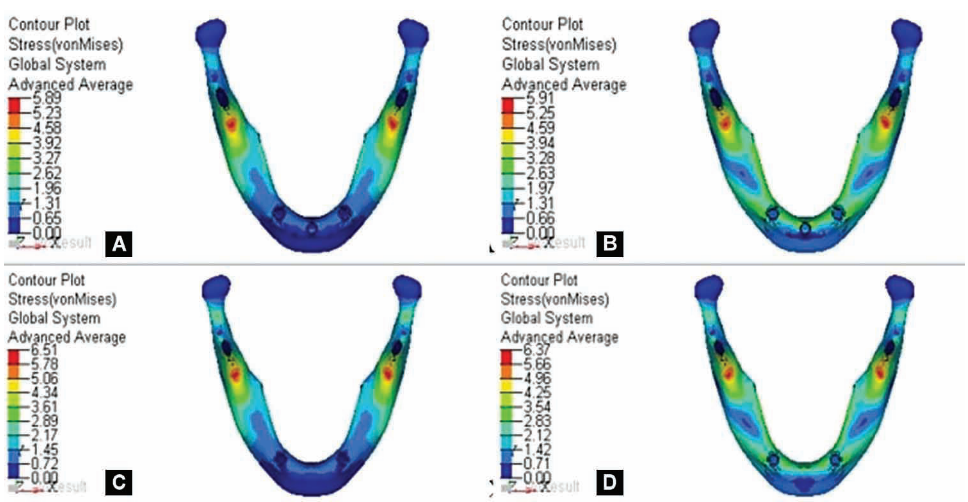
Even though more sophisticated alternatives like fixed implant prostheses are available and desirable for rehabilitating edentulous

Table 1: Numerical results for the VMS observed under axial loads at various positions in the denture load-bearing areas when two attachments are used to retain the overdenture

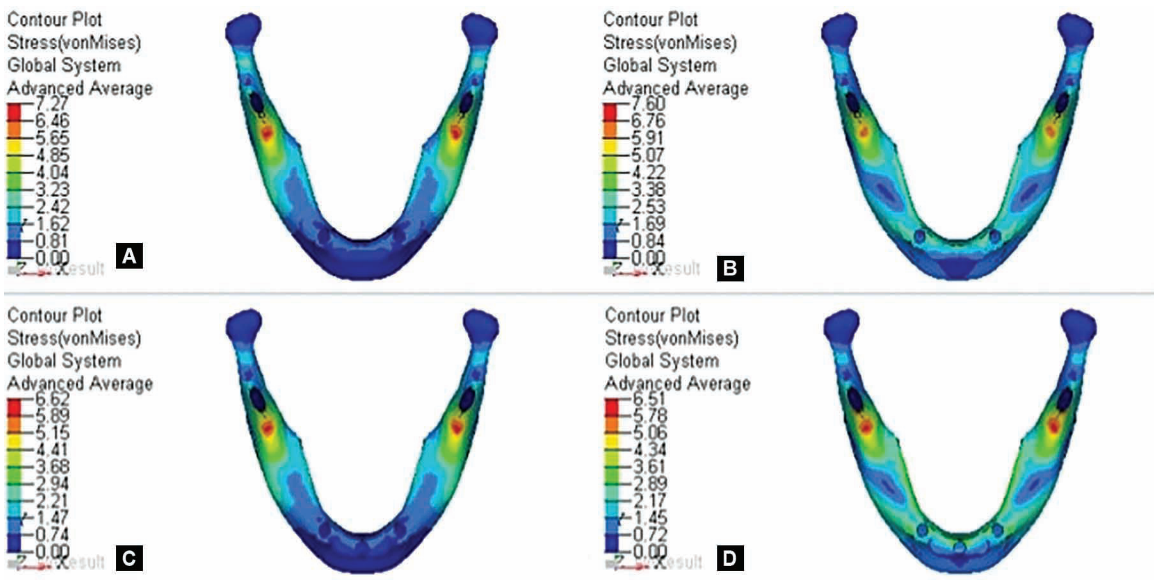
	Denture	*Mucosa*	*Attachment*	*Implant*	*Cortical bone*	*Cancellous bone*
Grade IV Ti ball	10	1.6	1.57	1.49	6.51	0.67
PEEK ball	10	1.6	0.73	1.92	6.51	0.67
Grade IV Ti locator	12.48	1.73	3	2.27	7.27	0.69
PEEK locator	12.48	1.73	0.43	7.36	7.27	0.69

Table 2: Numerical results for the VMS observed under axial loads at various positions in the denture load-bearing area when three attachments in tripod configuration are used to retain the overdenture

	Denture	*Mucosa*	*Attachment*	*Implant*	*Cortical bone*	*Cancellous bone*
Grade IV Ti ball	11.86	1.49	1.87	2.08	5.89	0.53
PEEK ball	11.87	1.49	0.48	1.85	5.9	0.53
Grade IV Ti locator	12.29	1.62	2.55	2.58	6.62	0.83
PEEK locator	12.29	1.62	0.39	7.36	6.63	0.9



Figs 3A to D: Stress in bone distal to implants subjected to three and two ball attachments made of grade IV Ti and PEEK under axial loads; (A) With three ball attachments made of grade IV Ti; (B) With three ball attachments made of PEEK; (C) With two ball attachments made of grade IV Ti under axial loading; (D) With two ball attachments made of PEEK



Figs 4A to D: Stress in bone distal to implants subjected to two and three locator attachments made of grade IV Ti and PEEK under axial loads; (A) With two locator attachments made of grade IV Ti under axial loading; (B) With two locator attachments made of PEEK under axial loading; (C) With three locator attachments made of grade IV Ti under axial loading; (D) With three locator attachments made of PEEK under axial loading

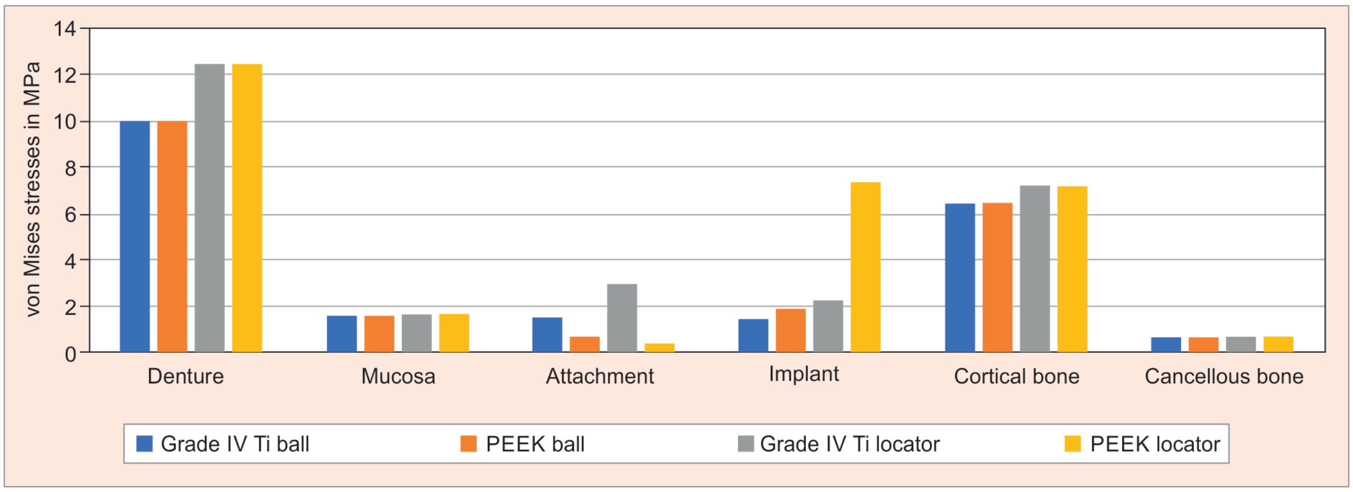


Fig. 5: Comparison of VMS generated with the double ball and locator attachments

cases with highly resorbed mandibular ridges, they are quite expensive. An economically feasible and functionally sound solution is IRO.[1]

To manage the long-term deleterious effects of IRO on the distal residual bone, in the current study, two different designs and biomaterials for attachments and two different implant placement configurations were investigated and subjected to loading as per the experimental protocol. The null hypothesis was rejected as the attachment design, material, and implant number had an influence on the stress distribution pattern in bone distal to the implant sites.

Titanium (Ti) and its alloys have been used in implantology since their inception. However, owing to its higher elastic modulus (modulus of elasticity), it is postulated to induce more stresses in the foundation bone due to extreme rigidity. PEEK, on the contrary, is expected to cause less stress in the bone and act as better conduits for force transmission from the prosthesis *via* the implants to the bone.[19–21] The implant configuration routinely used for an implant retained mandibular prosthesis is the placement of two implants at A and E, positions as classified by Misch in mandibular overdenture classifications.[9] This arrangement establishes a fulcrum connecting the points A and E, which makes a hinge type of prosthesis movement (PM) rampant and has deleterious effects on the anterior and posterior ridge due to hydrostatic pressure buildup, causing accelerated resorption in the bone distal to the implant sites.[2] In comparison to that, a three-implant configuration at the Misch sites A, C, and E[9] on the application of the masticatory forces is postulated to cause reduced PM. When the forces are applied anteriorly, the sole anterior implant impedes the tissue-ward movement of the prosthesis, and when forces are applied posteriorly, the two distal implants retard the tissue-ward movement of the prosthesis, decreasing the mucosal trauma and cellular edema, thus retarding the bony resorption.[9]

As per the results of the current study, locator attachments displayed stress accumulation of higher orders in the denture, mucosa, the attachment itself, the implant, and also the supporting bone. The same inference was observed in both the two-implant

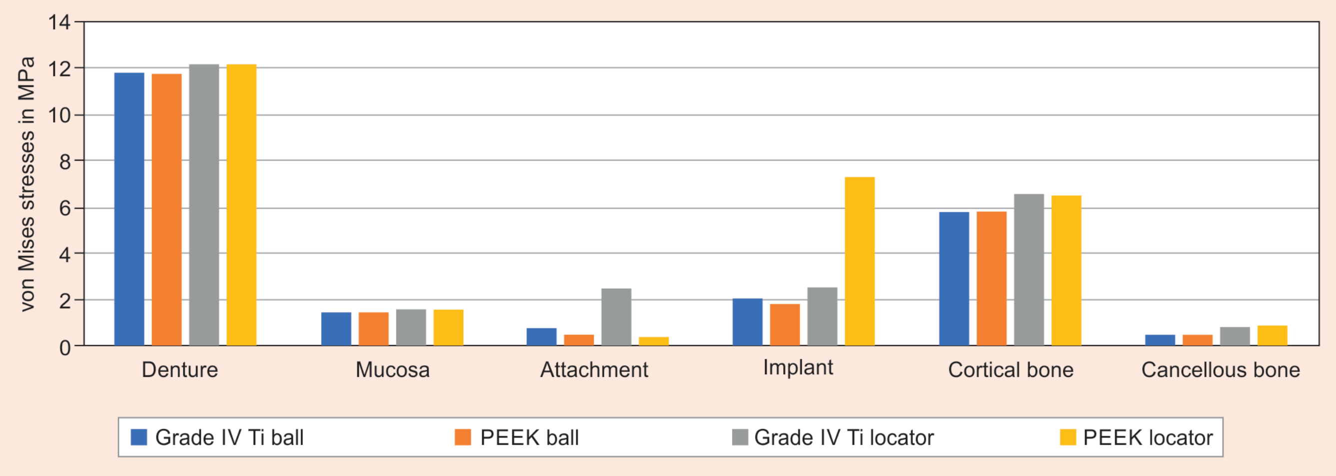


Fig. 6: Comparison of VMS generated with tripod ball and locator attachments

and three-implant configurations, but the magnitude was lesser in three implant configurations in all the locations but the distal cancellous bone, where the difference was not very significant. This showed that the three implant systems have a much more favorable stress profile on the posterior mucosa and bone which is the prime area for residual ridge resorption. Higher levels of stress that were observed with the use of locator attachments are inconsistent with some previous literature[4,22] but consistent with some articles published before.[3] A possible reason for this conflict could be the unique matrix-patrix relationship of the locator attachments and the shape of the ball attachment, which has been suggested to be prone to absorbing more stresses and dissipating less to the implant.[3]

The results also showed that the attachments made out of grade IV Ti concentrated a significant amount of stress within their bodies and passed on marginal stresses to the implant below. The attachments made of PEEK showed an immense reduction in stress concentration, owing to which the implants below were subjected to higher stresses of the order of 7.36 MPa which are nearer to the critical values for fracture toughness of Ti alloy-based implants.[23] The alarming finding of PEEK attachments was the concentration of stresses within the implant fixture at the neck area that made the implant-abutment junction particularly prone to fractures under cyclic loading. This trend was duplicated in the three implant configurations as well, which suggested that the use of PEEK for attachments and Ti alloys for fixtures could lead to stress incorporation in implant fixtures and might cause implant micro-fracture under repeated loading.[24] As a future scope of this study, the researchers could use PEEK material for both the implant fixture and the attachment and compare the results with the results of the current study. The use of PEEK for implant fixtures, as well are postulated to cause lesser stress accumulation within the implant system and also generate a greater and time-controlled release of forces to the peri-implant and distal bony zones after getting dampened, reducing abuse atrophy. When similar kinds of materials are used both for the implant body and for the attachment, the load sharing of the system is hence theorized to be better biomechanically.[25]

Discussing the different implant configurations used for the current study, it was shown that the placement of three implants at A, C, and E positions instead of two implants at A and E positions showed a more favorable stress profile.[9] In the two-implant configuration, more stresses were seen in the distal bone and mucosa, and comparatively lesser stresses were generated in the implant attachment assembly. Since the implant systems have higher fracture resistance and toughness as compared to the mucosa and the pliable bone, it is advisable to subject the implant components to more stresses and the biological systems to relatively lesser forces.[24] As deduced from the results keeping the parameters of the current study under observation, it was observed that the combination of three implant configurations using ball attachments to retain and partially support a mandibular overdenture displayed the most favorable stress profile for better long-term prognosis and prosthetic success. As is expected, increasing the number of implants increases the amount of support derived for the prosthesis from the implants and in turn decreases the support derived from the posterior bone and mucosa.[7] More the number of implants better the support and stress profile, but the three-implant design is surgically less invasive, more convenient economically, and biomechanically more favorable. Nevertheless, the introduction of an increased number of implants in the assembly and analysis of the generated stress patterns in the distal bone is also a future possibility.

The finite element models were made of uniform density and quality, whereas the actual materials may contain impurities and pores, which may cause errors. The boundary conditions are also difficult to be satisfied in intraoral conditions. Thus, keeping the limitations of the procedure of FEA[26,27] in view, it can be deduced that the current study is good for comparative analysis of VMS at different locations of the models. It did not, however, provide any absolute, irrefutable data. Hence, long-term clinical trials are strongly suggested to correlate the findings of the study with the results obtained clinically.

Conclusion

Within the limitations of the study, the following conclusions were drawn—the geometry or design of the attachment does influence the stresses generated in the bone distal to the implants. The material used for attachment fabrication does not influence the stresses generated in the bone distal to the implants, but it does influence the stress concentration seen in the implant fixtures in the implant abutment junction area. The three-implant configuration showed a better stress profile in the target area of the study as compared to the two-implant configuration. The most favorable combination, according to the current set of parameters in this study, was a three-implant configuration using PEEK ball attachments for abutments.

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