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Three-dimensional finite element analysis of stress distribution on different complex macro designs in commercially available implants: An in-vitro study

Saranya V [a], Mervin Harris [a], Silpa Abraham [a], Ramanarayanan Venkitachalam [b], Shiv Shankar Nair [c], Anil Mathew [a,*]

[a] Department of Prosthodontics and Crown & Bridge, Amrita School of Dentistry, Amrita Vishwa Vidyapeetham, Kochi, Kerala, India
[b] Department of Public Health Dentistry, Amrita School of Dentistry, Amrita Vishwa Vidyapeetham, Kochi, Kerala, India
[c] FEA Consulting Engineer, Amrita TBI, Amrita Vishwa Vidyapeetham, Amritapuri, Kollam, Kerala, India

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ABSTRACT

Objective: This study aimed to investigate the effects of different commercially available complex implant macro designs on stress distributions using Finite element analysis. The experiment is done under varying simulated bone conditions to provide reference for clinical application.
Materials and methods: The study employed the Finite Element Analysis (FEA) method to compare four commercially available complex implant macro designs on a Computer-Aided Design (CAD) model of a maxillary bone segment. The three-dimensional geometrical model of the implants was reconstructed from computed tomography (CT)-slices in Digital Imaging and Communications in Medicine (DICOM) format and contact condition between the implant and the bone was considered as 'Bonded', implying perfect osseointegration. All materials used in the models were assumed to be isotropic, homogeneous, and linearly elastic. The Finite element simulations employed load of 400 N under both axial and non-axial conditions Stresses were analysed under different bone conditions.
Results: Average values of von Mises stresses were used for comparing stress levels between implant designs. There was a definite increase in the equivalent stress values from higher density(D1)to lower density (D4) bone conditions for all implants. The percentage of increase ranged from 23.63 to 49.39 on axial loading and 20.39 to 57.19 when subjected to non-axial loading. The equivalent stress values resulted from non-axial loading were 1.78–2.94 times higher than that of axial loading for all implants under all bone densities. Among the complex designs Equinox Myriad Plus implant exhibited the least stress under axial loading (12.749–19.046 MPa) and (37.462–49.217 MPa) for non-axial loading. The stress on the crestal module was higher (1.49–2.99 times) than the overall stress on the implant regardless of the loading direction or bone conditions.
Conclusions: Data from the present study shows Equinox Myriad Plus implant generating the least equivalent stress and this can be taken as indicator in the biomechanical performance of the design.

1. Introduction

In the recent decade, Osseo integrating dental implants have become a reliable option for replacing missing teeth.[1] Traditional crown and bridge approach have been replaced by the implant treatment modality so that adjacent natural teeth are kept unharmed.[2] Over the past 10 years success rate of implants has been reported to be 90 %–95 %.[3] Of the implants that fail, 35 % is due to poor quality of bone.[4] Osseointegration is the primary determinant for implant success, which is influenced by factors such as surgical technique, host bed, implant design, surface, material biocompatibility and loading conditions.[5]

Dental implant is designed in such a way to manage, dissipate and distribute the biomechanical forces.[6] Design feature can be broadly classified into macro and micro designs.[7] Macro design of the implant includes the body shape, crestal module and the thread design (thread geometry, thread pitch, thread depth, face angle, thread helix angle).[8]

* Corresponding author. Department of Prosthodontics and Crown & Bridge, Amrita School of Dentistry, Amrita Vishwa Vidyapeetham, Ponekkara P.O., Kochi, Kerala, 682041, India.
E-mail address: dr.anilmathew.aims@gmail.com (A. Mathew).

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Implant macro design play an important role in optimization of forces.[9] Thread design also enhance initial contact, increase surface area and has an influence on insertion torque and primary stability. Certain thread shape plays an important role in minimizing stress concentration. Thread depth and width also influences the total implant surface area which is an important determinant for stress distribution.[10] Stresses are more sensitive to thread pitch in cancellous bone.[11] Maximum effective stress was found to decrease with the gradual decrease in the thread pitch.[12] Depending on the shape, different face angles are generated on the implant. This face angle can change the direction of forces at the bone implant interface.[13] The thread lead determines the speed in which an implant will be placed in bone.[14] Thread helix angle grows according to the thread lead, resulting in a potential effect on the forces transmitted to the bone.[15] The commercially available implant designs are created by the amalgamation of these design features in varying combinations. Thus, to evaluate the reliability and effectiveness of the resultant patterns, stress analysis at bone-implant interphase become mandatory. The behavior of endosteal dental implants can be investigated by numerical techniques like finite element analysis method to predict stress and strain distributions at peri-implant regions by modeling in different scenarios.[16–19] This numerical simulation technique provide accurate results depending on mesh quality, data precision, and boundary/loading conditions.[20] Literature states that 3D FEA studies aligned well with in vivo strain gauge measurements and clinical outcomes.[21] In vivo clinical studies though gold standard have been limited in the literature owing to the complex nature and confounding factors.[22]

Considering the potential of macro design features for optimization of biomechanical forces, several implant designs are available commercially. These complex macro designs by different manufacturers claim for better stress distribution in different types of bone but data regarding the comparative evaluation among them is sparse in the literature. This study intends to assess the effect of different commercially available complex implant macro designs on stress distributions using finite element analysis.

2. Materials and methods

The study utilized the Finite Element Analysis method to compare four commercially available implants with varying complex macro designs: Adin Touareg Close Fit implant, Nobel Active RP, Equinox Myriad Plus implant, and Straumann Tapered Effect implant holding Indident implant with a simple cylindrical design as control. Descriptions of the implants and their sample numbers are provided in Fig. 1. Implants of nearly similar size were selected.

Sample No.	Implant System	Design Specifications
1	Adin Touareg Close Fit Implant	Tapered implant body, double and triple threads, three different thread pitches, spiral thread shape, lowest thread pitch in the crestal module increasing towards the apex and cutting edge in the apical region.
2	Equinox Myriad Plus Implant	Tapered implant body, anaform root shape design, bioprofile thread, micro threads in the crestal module, double threaded in the middle, reverse buttress thread shape and cutting edge in the apical region.
3	Indident Implant	Cylindrical implant body, smooth crestal module, uniform thread pitch and buttress thread shape.
4	Noble Active RP Implant	Tapered implant body, roughened crestal module, double threaded in the middle region, spiral V thread shape and cutting edge in the apical portion.
5	Straumann Tapered Effect Implant	Tapered implant body, uniform thread pitch, V thread shape and cutting edge in the apical portion.

Finite element analysis was conducted on a CAD model of a maxillary bone segment, representing the premolar/molar region, with separately sectioned cortical and cancellous bones featuring implants. All implants underwent Micro Computed Tomography (micro-CT) scanning at the Indian Institute of Science in Bangalore, India. The three-dimensional geometrical model of the implants was reconstructed from DICOM format CT slices of 7-μm thickness using image segmentation and faceted 3D reconstruction with Materialise Mimics Research 20.0 (Materialise Corporation, USA). The generated faceted CAD model was converted into a solid CAD model and idealized with the bone block using Spaceclaim 2016 (Spaceclaim Corporation, USA). The contact condition between the implant and the bone was considered as 'Bonded', implying perfect osseointegration between the implant and surrounding parts, as bonded contact assumes no movement between components. The CAD was imported in Parasolid format to ANSYS Mechanical R19.0.

The model was meshed with an appropriate mesh size. The desired number of elements and nodes were determined after conducting a mesh convergence study. A refined mesh was used for the implants, while a comparatively coarse mesh was assigned to the bone block. The three-dimensional finite element model, corresponding to the geometric model, was meshed using ANSYS Mechanical (ANSYS 19.1), resulting in 124,658 nodes and 103,794 elements. As a first approximation, all materials used in the models were assumed to be isotropic, homogeneous, and linearly elastic. For accurate analysis and interpretation of the results, two material properties, namely Young's modulus and Poisson's ratio, were utilized to describe the mechanical behaviour of the complete model.

Boundary conditions were applied to ensure sufficient fixed nodal displacements, preventing the structure from moving as a rigid body when loads were applied. Finite element simulations for the implants were developed, considering static axial loads uniformly applied on the

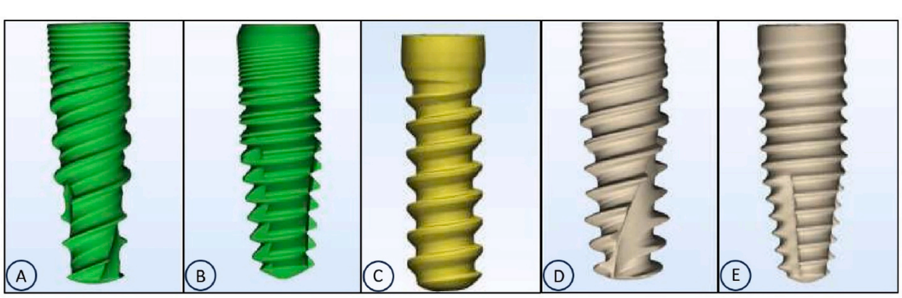

Fig. 1. A) Sample 1 - Adin Touareg Close Fit, B) Sample 2 – Equinox Myriad Plus implant, C) Sample 3 – Indident Implant, D) Sample 4 – Nobel Active RP, E) Sample 5 – Straumann Tapered Effect Implant.

entire fixed prosthesis. A load of 400 N was applied under both axial and non-axial conditions.

Stresses were analysed under different bone conditions (D1, D2, D3, and D4). An example is provided in Fig. 2, where equivalent stresses for all implants are analysed in D3 bone under axial and non-axial loading. Equivalent (von Mises) stresses, shear (maximum shear stress), compressive (minimal principal stress), and tensile stresses (maximum principal stress) were derived for each implant. The complete FEA was conducted using the 3-D FEA program ANSYS R19.1 (ANSYS Inc., Canonsburg, PA, USA).

3. Results

All scanned implant models were subjected to a force of 400N in both axial and non-axial (45°) loading, and results were obtained under varying bone density conditions from D1 to D4. Equivalent (von Mises) stresses, shear, compressive, and tensile stresses were calculated for each implant. Average values of von Mises stresses were used for comparing stress levels between implant designs.

Equinox Myriad Plus implant exhibited the least stress under axial loading (12.749–19.046 MPa), and Indident, the control did so under non-axial loading (28.128–44.211 MPa) when tested in D1 to D4 bone conditions. Equinox Myriad implant was showing the least (37.462–49.217 MPa) among complex implant designs. The highest stress was displayed by the Adin Touareg Close Fit implant (22.805–28.193 MPa) under axial loading and by Nobel Active RP implant (58.205–76.547 MPa) under non-axial loading under the same conditions.

There was a definite increase in the equivalent stress values from D1 to D4 bone conditions for all implants. The percentage of increase ranged from 23.63 to 49.39 on axial loading and 20.39 to 57.19 when subjected to non-axial loading. The equivalent stress values resulted from non-axial loading were always higher than that of axial loading for all implants under all bone densities. Analysis showed the former was 1.78–2.94 times higher than the later (Fig. 3).

Similar observation was found in constituent stresses, except for shear stress values under axial loading, which showed variable results for different bone conditions.

The assessment of the von Mises stress values revealed that maximum stress concentration on the implants were in the crestal module region for all designs irrespective of the loading direction or bone conditions. The stress on the crestal module was 1.49–2.99 times higher than the overall stress on the implant (Supplementary Table 1.). Specific analysis of the individual designs revealed Indident and Equinox Myriad Plus implant having the lowest stress values and Nobel Active RP implant the highest under both axial and non-axial loading (Fig. 4).

Minimum principal stress (tensile stress), maximum principal stress (compressive), and shear stress values were calculated for all implants. In compressive stress, Equinox Myriad Plus implant was found to have the highest value under axial loading, and Nobel Active RP implant had the highest under non axial loading, while Indident showed the lowest

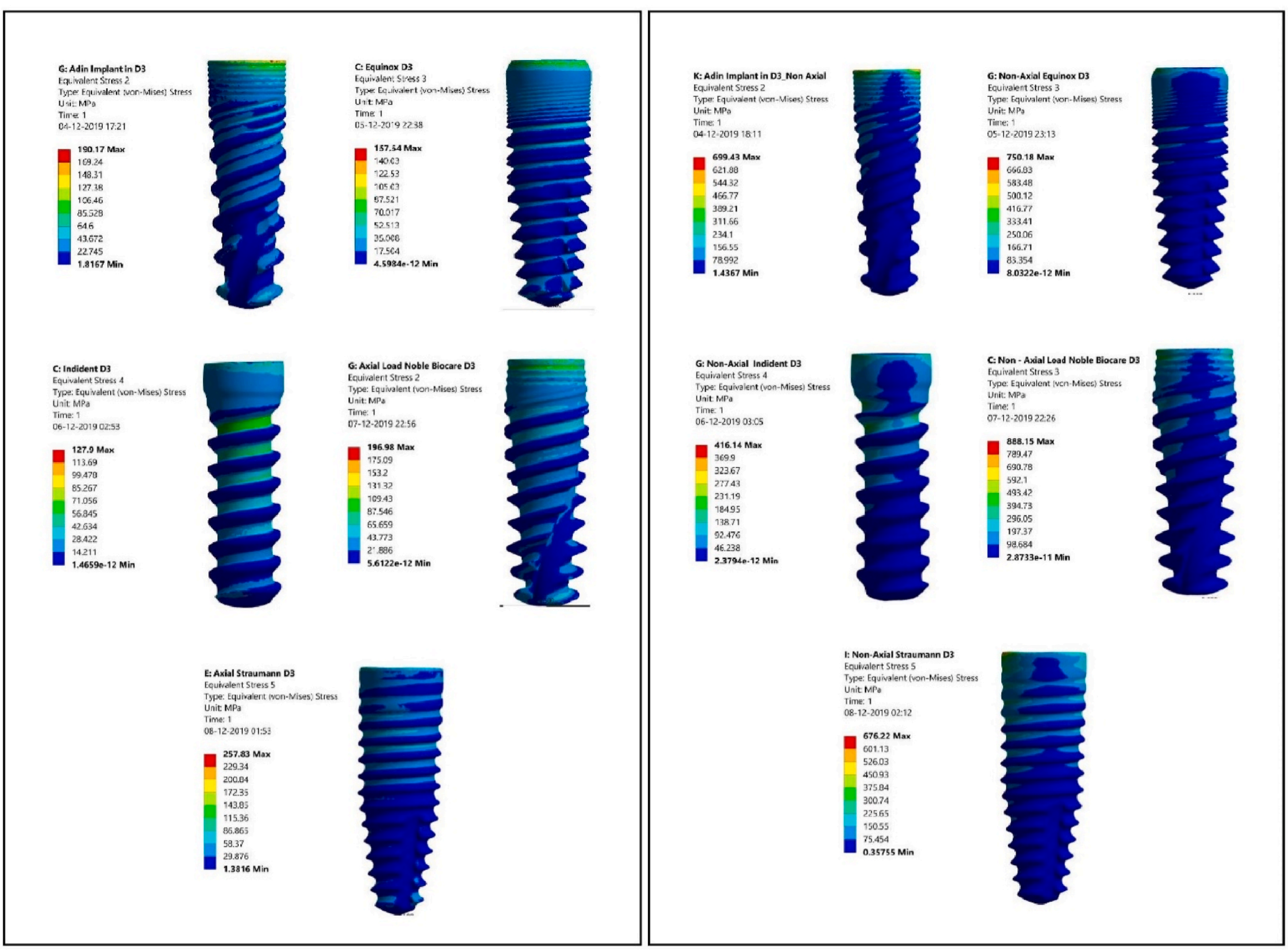

Fig. 2. Equivalent stress stresses in D3 bone under axial and non-axial loading.

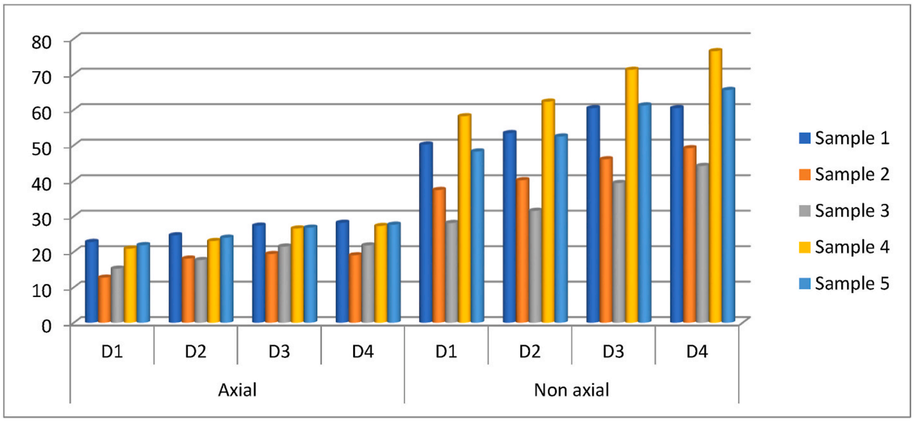

Fig. 3. Equivalent stress on implants.

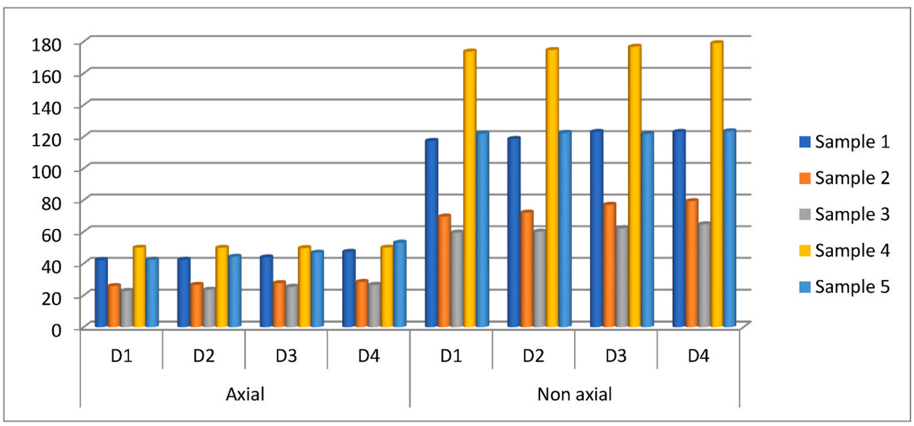

Fig. 4. Equivalent stress on implant crestal module.

values for both conditions. In shear and tensile stresses, Indident had the lowest value under both axial and non-axial loading. Straumann Tapered Effect Implant recorded the highest under axial loading, and the Nobel Active RP implant had the highest for non-axial loading in the same scenario.

4. Discussion

From a biomechanical perspective, occlusal forces can lead to physiologic adaptation if within the normal range. However, excessive stress which is also called an implant overload can cause loss of osseointegration and finally leads to prosthetic failure.[23] The stress in the bone surrounding an implant is influenced by the macroscopic design of the implant like body and thread geometry.[24] Compressive force can improve bone density and strength whereas, tensile and shear stress are least beneficial and weakens the bone.[25] The crestal module and collar designs are also important macroscopic part of implant as they are the region of concentrated mechanical stress. A crestal module design with angled geometry or groves coupled with surface texture can increase bone contact and will impose compressive stress on surrounding bone thus preventing the risk of marginal bone loss.[26]

The study was conducted using Finite element analysis which is considered an acceptable tool to stimulate biomechanical performance of various dental implant designs on peri-implant bone.[27] FEA results are presented as stresses that are generated in the investigated structures. These stresses may occur as tensile, compressive or shear. It can also be presented as a stress combination labeled as equivalent or Von Mises stresses that depend on the entire stress field and are a widely used indicator for the likelihood of damage occurrence. Thus the latter is considered in this study for comparison.[28–30]

Components in a dental implant-bone system are exceptionally complex geometrically, making it difficult to achieve any analytical solution. Numerical methods such as FEA has been viewed as the most suitable tool in this condition to calculate the material stress in situations represent the clinical reality. Data generated from literature, 3D scanners, or computer tomography as anatomic model is converted in a parameterized model by the Computer Aided Design (CAD) software and finally it is converted in a discretized model by the FEA software. Owing to the generalization of the source anatomically simplified models reflect average measurements of a population.

The type interface between the implant in the study was assumed as bonded since the objective was to assess and compare the functional performance of different implant designs.[27] Static loading was simulated both in axial and non-axial directions to explore the influences of implant designs on stress transfer and distribution. The study attempts for a quantitative comparison of stress distribution between different commercially available complex macro designs of dental implants for an applied load in different bone densities. This may give an insight in to the projected biomechanical environment and help to prioritise the design according to clinical scenario. The samples tested had similar dimensions and Indident implant (Sample 3) with cylindrical geometry and simple square shaped thread design was considered as control.[31] The conversion of a single occlusal force into 3 different types of forces is largely controlled by the implant geometry. There should be a balance between the compressive and tensile forces which minimize the shear forces that is generated.[31]

This study showed a definite increase in magnitude of stress with reducing bone density. The equivalent stress values showed an increase of 23.63–49.39 % on axial loading and 20.39–57.19 % when subjected to non-axial loading from D1 to D4 bone. This observation was similar in all samples and consistent with the earlier studies by Yang Liu et al.[32] Among the samples Equinox Myriad Plus implant showed the least equivalent stress values on axial loading (12.749–19.046 MPa). Indident implant, the control recorded 15.279–21.828 MPa which was closer to and displayed the least values on non-axial loading (28.128–44.211 MPa). Equinox Myriad Plus implant was its closest contender (37.462–49.217 MPa) in this also. Highest was by displayed by Adin Touareg Close Fit impant (22.805–28.193 MPa) under axial loading and by Nobel Active RP implant (58.205–76.547 MPa) under non axial loading. Since Von Mises stresses represent entire stress on the field and accepted marker for probable damage occurrence,[28–30] these observations can be taken as indicator in the biomechanical performance of the design.

Literature states that compressive stress have a favourable influence on bone tissue up to a certain limit as it improves bone formation[33] and bone density over time.[32] In the present study, compressive stress was found to be higher for complex tapered designs. Equinox Myriad Plus implant found to have the highest value under axial loading in dense bone. While Adin Touareg Close Fit implant showed higher values in lesser density. Nobel Active RP implant and Adin Touareg Close Fit implant were high in non-axial loading. It was difficult to recognize a specific pattern between different complex designs and varying bone densities. Control implant Indident with simple cylindrical design showed least values for both conditions(Supplementary Table 2.). Since literature has conflicting reports on the relation of compressive stress to geometry,[34] the result may be explained only as the outcome of the total design.

As in the earlier literature this study also elicited an increased Von mises stress values under inclined loading compared to the vertical.[32] Analysis showed the former was 1.78–2.94 times higher than the later, the ratio found to be similar in all bone conditions(Supplementary Table 3.). The consensus on rate of increase according to bone density is not existing[32,35] and this adds to the cluster.

Crestal module is the transition zone between the prosthetic component and its load bearing implant body. Consequently, its design become critical because of the location in relation to the alveolar crest, and abutment implant interface.[36–38] The results were in concurrence with the earlier literature regarding the stress concentration in the crestal module region[30,32,39] and found to be 1.49 to 2.99 times higher than the overall stress on the implant. Equivalent stress found to be minimum in control and Equinox Myriad Plus implants (Supplementary Table 4.).

The retentive elements like micro threads and roughened surfaces increase osseointegration, reduce marginal bone loss on loadings and this concept banks on the mechanical link created between bone and implant averting the stress contour on the interphase and transfer adequate forces leading to the stimulation of an osseous tissue and maintenance of crestal bone height as per the Wolff's law.[40]

On the other hand, these micro threads have a threshold and is formerly established by finite element analysis that higher amplitudes lead to failure. The effect of Von Mises tension generated on threaded crestal module in reduction of bone density is validated through comparative analysis between histological and computerized images.[39,41] Thus a crestal module design circumventing high levels of cervical loads and aid in distributing the mechanical stress homogenously at the interface is favoured for integration.[42,43]

4.1. Limitations of the study

Being a finite element analysis this study does not reflect exact clinical situations, but only aid in understanding the influence of implant designs on the transmission of loads to both bone and implants. As in many other FEA studies this experiment also consider biological materials as isotropic, linear, and elastic. Though this anatomically simplified models with average measurements of a population can reduce the "noise" that may conceal the relevant results the risk for inaccuracy is to be considered. Thus it is mandatory to contrast these results with in-vivo studies.

5. Conclusion

Considering the background and data from the present study Equinox Myriad Plus implants (Sample2) delivered lesser magnitude of equivalent stress on the bone implant interphase and has better prospects compared to other complex variants. Finding from the literatures and this study can be put forward to design an ideal implant which can reduce the shear stress at bone implant interface and provide more compressive load transfer, which is important in compromised bone densities and higher force magnitudes. A combination of certain characteristics in the macro design of implant like wider crestal modules with micro threads, decrease in thread pitch and increase in thread depth, rounded or 'V' shaped thread profile to increase load bearing area (LBA), tapered implant shape with groove and flat apical end can offer better primary stability and allows to adopt immediate loading protocol in compromised conditions too. Detailed corroboration with animal experiments and comparative analysis between histological and computerized images are mandatory to reach any conclusion.

Patient consent

Not applicable as it is an invitro study

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Nil.

Author contribution

SV: acquisition of data, interpretation of data, final approval of the version to be published, MH: drafting the article, revising article critically, final approval of the version to be published, SA: drafting the article, revising article critically, final approval of the version to be published, VK: data analysis, final approval of the version to be published, SSN: data analysis, final approval of the version to be published, AM: conception and design of the study, interpretation of data, revising article critically, final approval of the version to be published.

Ethics statement

Study protocol was approved by the Institutional Ethical Committee of Amrita Institute of Medical Sciences. (IRB-AIMS-2018-072).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobcr.2024.10.003.

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