Optimizing short dental implants: Impact of macro thread designs and platform configurations on stress distribution and micromotion- A three-dimensional finite element analysis

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ABSTRACT

This study investigates the impact of implant thread designs and abutment platform configurations on stress distribution and micromotion in immediately loaded short implants within D2 and D4 bone densities using finite element analysis (FEA). Three-dimensional FEA models simulated implants with varying thread designs (single, double, triple, asymmetrical) and two platform configurations (platform-switched, regular). A static load of 100N at a 25° angle was applied to analyze von Mises stress and micromotion at the bone-implant interface in the cortical bone. Results indicated that single-threaded implants generated the highest stress, while platform-switched configurations generally reduced stress, particularly in D2 bone. Triple-threaded implants exhibited the least micromotion across both bone densities. Although platform-switched implants showed reduced micromotion, differences were not statistically significant. The study underscores the importance of implant design in stress distribution and micromotion, with asymmetrical and triple-threaded designs with platform-switched configurations showing promise. Despite these findings, further research, including dynamic simulations and clinical trials, is necessary to optimize implant designs for improved long-term stability.

Keywords: Atrophic ridge, Short, Dental implants, Immediate dental implant loading, Finite element analysis.

INTRODUCTION

The search for ideal replacements for missing teeth has been a significant challenge for dental practitioners over millennia, leading to the development of dental implants by Per-Ingvar Brånemark in the 1950s, who famously stated, "No one should have to die with their teeth in a glass of water beside their bed." Initially employed to stabilize loose dentures, dental implants have evolved to address a range of needs, from single-tooth replacements to full arch rehabilitations.

Modern implant designs address challenges such as inadequate bone volume, particularly in areas with atrophied bone or maxillary sinus pneumatization. In these situations, short dental implants simplify treatment and reduce costs compared to complex surgical procedures for vertical bone augmentation.[1]

Moreover, the effectiveness of load transfer at the bone-implant interface depends on factors such as loading type, material properties, implant geometry, surface topography and bone quality.[2] Innovations like tapered configurations and varied thread patterns have been developed to enhance primary stability and optimize stress distribution.[3] Thread designs that maximize initial bone contact, primary stability, surface area and stress dissipation are crucial for improving osseointegration success rates.[4]

Osseointegration is a critical process whereby dental implants become integrated with the surrounding bone. The success of osseointegration can be significantly influenced by surface modifications to the implant.[5,6] Further, different thread designs, including single-thread, double-thread, triple-thread and asymmetric configurations, enhance mechanical engagement and primary stability. Platform-switching techniques, where the abutment is narrower than the implant platform, help preserve crestal bone levels and reduce marginal bone loss, thereby enhancing long-term stability and aesthetics.[7]

The timing of loading protocols, whether immediate, early, or delayed, is another critical aspect of optimal healing and integration. Immediate loading reduces treatment duration but introduces the risk of micromotion, which must be managed to ensure successful osseointegration and implant stability.

Finite Element Analysis (FEA) has played a crucial role in implant dentistry since 1976 when Weinstein et al. first applied it to this field.[8] To predict biomechanical performance and assess clinical parameters in implant dentistry, finite element analysis is used.[9] Recent advancements in computational power have enabled sophisticated simulations, including patient-specific models, thereby improving implant treatment planning and outcomes.

The study aimed to investigate how different macro thread designs and platform configurations influence stress distribution and micromotion around immediately loaded short dental implants using 3D finite element analysis and the objectives were to assess and compare the effects of various implant thread designs (single-threaded, double threaded, triple threaded, and asymmetric) and platform configurations (platform switched and regular) on the stress distribution in peri-implant hard tissue under oblique loading in two types of bone (D_2 and D_4), as well as to evaluate and compare how these implant thread designs and platform configurations affect micromotion in D_2 and D_4 bone densities. The null hypothesis was:

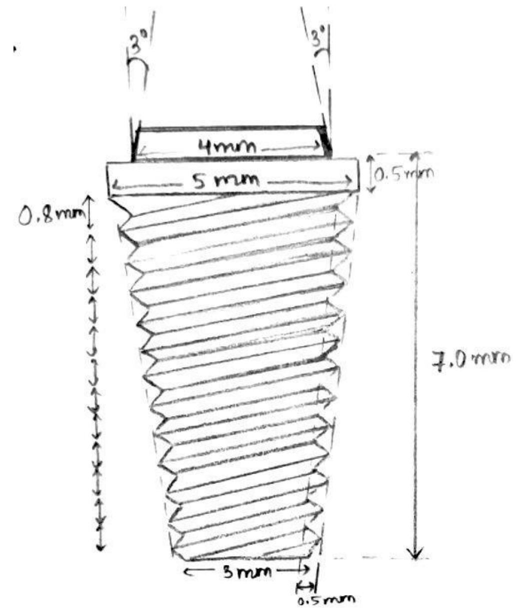
(a) There is no effect of implant thread designs and implant abutment platform configurations on the stress distribution in peri-implant hard tissue under oblique loading in both D_2 and D_4 bone densities.

(b) There is no effect of implant thread designs and implant abutment platform configurations on the micromotion of the implant under oblique loading in both D_2 and D_4 bone densities.

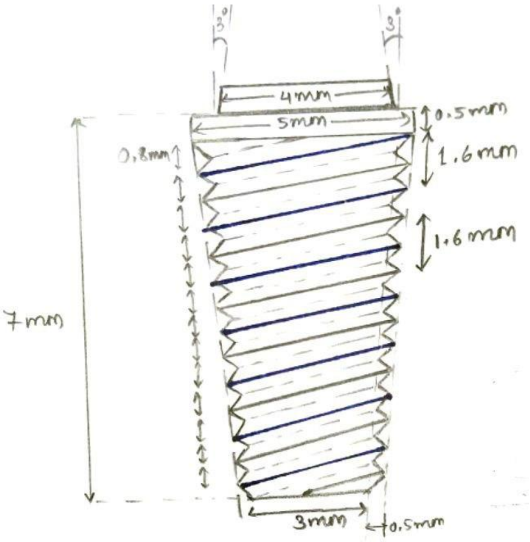
MATERIALS AND METHODS

This in-vitro experimental study was carried out in the Department of Prosthodontics And Crown & Bridge at Subharti Dental College & Hospital, Meerut, Uttar Pradesh, India. In this study, Solid Works 2023 (Dassault Systèmes Solidworks Corp.,Waltham, Massachusetts, USA) was utilized for CAD modeling and ANSYS 19.0 (ANSYS Inc., Canonsburg, PA) was employed for finite element modeling. The meshing process was carried out using Workbench Mechanical, while the analysis phase was conducted with ANSYS APDL (ANSYS Inc., Canonsburg, PA).

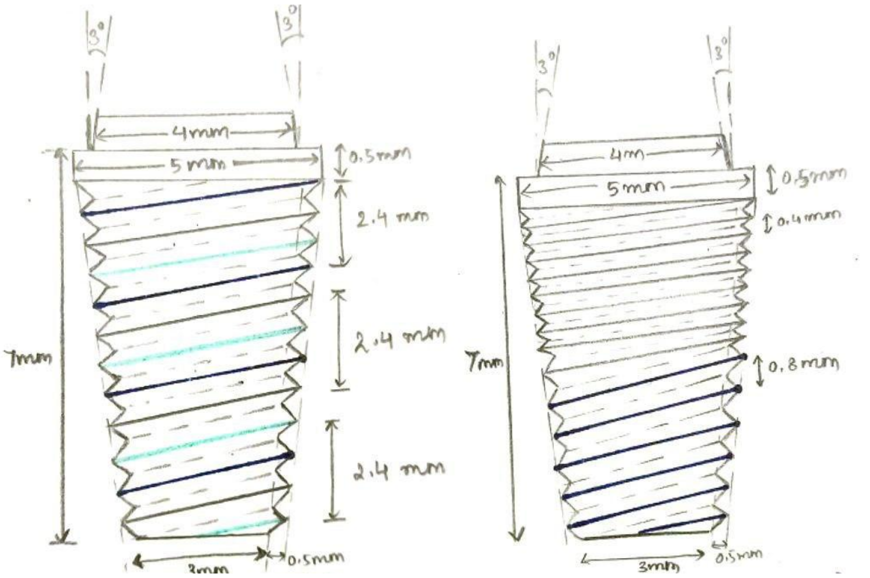
The 3D CAD models were designed for two implant-abutment configurations: platform-switched and regular platform with four thread designs- single-threaded, double-threaded, triple-threaded and asymmetrical for both configurations. Specifically, the implant fixture, being a short dental implant, had a diameter of 5mm and a length of 7mm. For the abutments, the platform-switched implant featured a diameter of 4mm (Fig.1), whereas the regular platform implant had a diameter of 5mm (Fig. 2). The bone models were designed as D_2 and D_4 bone types, based on the Misch classification (1990) (Table 1). Several assumptions were made regarding the mechanical properties (Table 2) of the simulated structures, including homogeneity, isotropy and linear elasticity, to facilitate the analysis.



Single Threaded

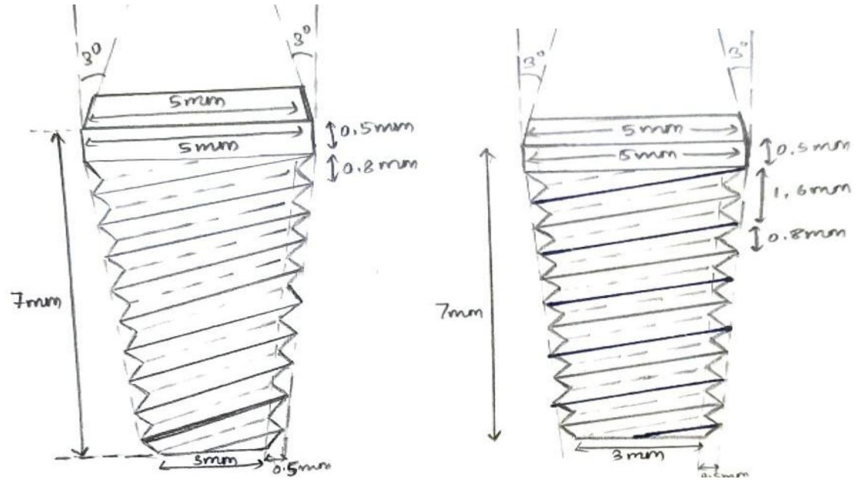


Double Threaded

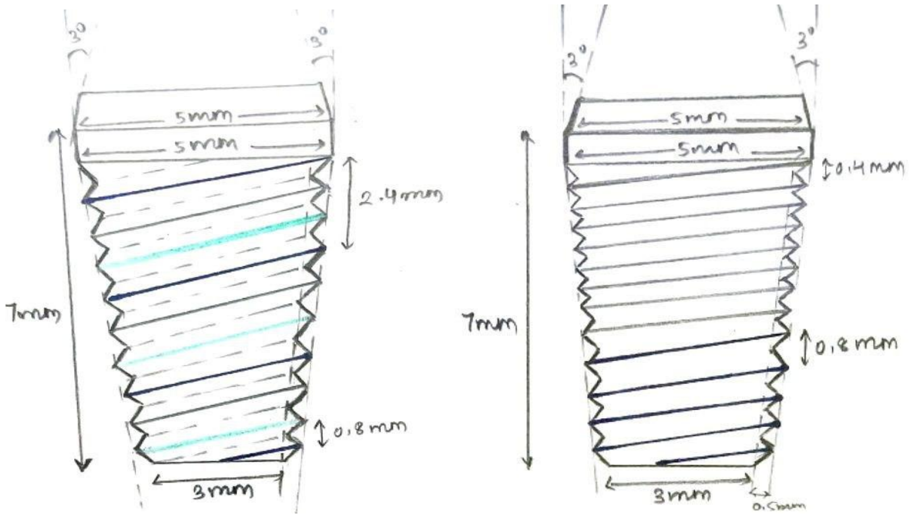


Triple Threaded **Asymmetrical**

Fig 1: Platform-switched Implant Abutment Platform Configuration.



Single Threaded **Double Threaded**



Triple Threaded **Asymmetrical**

Fig 2: Regular-platform Implant Abutment Platform Configuration.

Table 1: Bone Model

SL. No.	Bone quality	Bone model
1.	D_2	Thick compact bone (2mm) surrounding a core of dense trabecular bone.
2.	D_4	Thin layer of cortical bone (1mm) surrounding a core of low-density trabecular bone.

Table 2: Mechanical Properties

MATERIALS	YOUNG'S MODULUS (MPa)	POISSON'S RATIO
Titanium implant	103400	0.35
Cortical bone	13700	0.30
Cancellous bone (D2)	1370	0.30
Cancellous bone (D4)	231	0.30

METHODOLOGY

This study employed three-dimensional bone modeling to accurately represent the complex implant system within the bone. The peri-implant bone, an anatomical structure with varying density values, significantly influenced the stress concentration distribution following loading. Both cortical and cancellous bones were modeled as homogeneous, isotropic and linearly elastic materials to simplify the computational process.

The primary objective was to analyze the effect of macro thread designs and platform configurations on stress distribution and micromotion around immediately loaded short dental implants in D_2 and D_4 bone densities using three-dimensional finite element analysis (Table 3). Initially, short and wide implants of Ø 5.0 –7L, assembled with abutments of Ø4.0 in platform-switched and Ø5.0 in regular platform implants, were digitally simulated using Solid Works 2023 (Dassault Systèmes SOLIDWORKS Corp.,Waltham, Massachusetts, USA). These simulations also included D_2 and D_4 bone models (Table 4).

Table 3: Test Groups

PLATFORM SWITCHED			
GROUP 1	**GROUP 2**	**GROUP 3**	**GROUP 4**
SINGLE THREADED	DOUBLE THREADED	TRIPLE THREADED	ASYMMETRICAL

REGULAR PLATFORM			
GROUP 5	**GROUP 6**	**GROUP 7**	**GROUP 8**
SINGLE THREADED	DOUBLE THREADED	TRIPLE THREADED	ASYMMETRICAL

Table 4: Three-dimensional Structure of Dental Implants

IMPLANT THREAD DESIGN	PITCH (mm)	THREAD DEPTH (mm)	CORONAL IMPLANT DIAMETER (mm)	APICAL IMPLANT DIAMETER (mm)	PLATFORM SWITCH (mm)
SINGLE THREADED	0.8	0.5	5	3	1
DOUBLE THREADED	1.6	0.5	5	3	1
TRIPLE THREADED	2.4	0.5	5	3	1
ASYMMETRICAL					1
• CORONAL	0.4	0.25	5	3	
• APICAL	0.8	0.5	5	3	

In this study, the bone-implant interface was modeled as a non-linear frictional contact with a frictional coefficient of 0.3.[10] This meant that tensional forces were not transferred by contact zones; instead, only pressure and tangential frictional forces were transferred. The amount of interfacial sliding between the contact elements was calculated and analyzed to understand the interface behavior better.

To define the load, von Mises stress, an equivalent stress value used to determine material yield, was employed to analyze the loading forceseffect on the peri-implant area or prosthesis construction. A combined load, representing a more realistic oblique occlusal force, was used to induce the highest localized stress in the cortical bone. Each model was subjected to a 100N load applied obliquely at a 25-degree angle buccolingually, followed by a comparative analysis under immediate loading conditions in both D_2 and D_4 bone densities (Fig. 3).

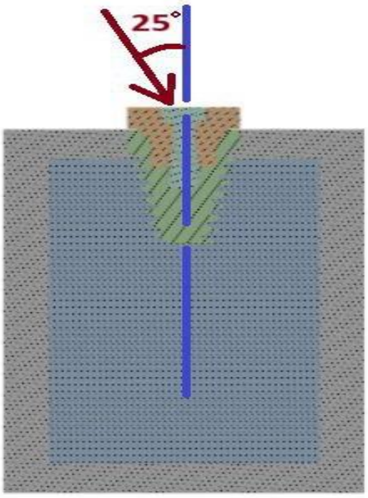


Fig 3: Assignment Of Load

The process of creating the mesh, elements, and respective nodes and defining boundary conditions is termed "discretization" of the problem domain. This aims to obtain a discrete model of a continuous object with a finite number of freedom degrees. A polygonal mesh, comprising vertices, edges and faces, was used to define the shape of polyhedral objects in 3D computer graphics and solid modeling. Following the assignment of material properties and load definitions, the mesh was verified before running the final analysis. The number of nodes and elements was incrementally increased until the difference in peak stresses between successive mesh refinements was 5% or less, thereby minimizing the geometric error characteristic of the mesh discretization process (Fig. 4).

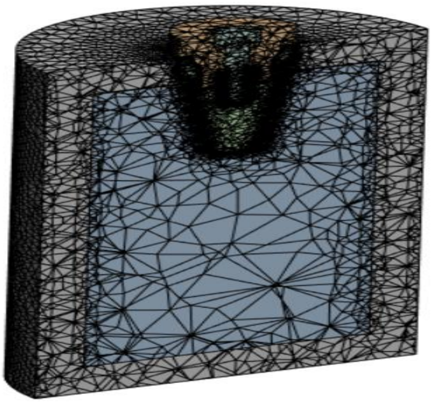


Fig 4: Meshing

The study evaluated the effect of loading on cortical bone through von Mises stress analysis, expressed in megapascals (MPa) (Fig. 5) and assessed implant micromotion in millimeters (mm) (Fig. 6). After data collection, the results were tabulated, statistically analyzed and compared. The finite element model was solved through structural analysis using ANSYS APDL (ANSYS Inc., Canonsburg, PA).

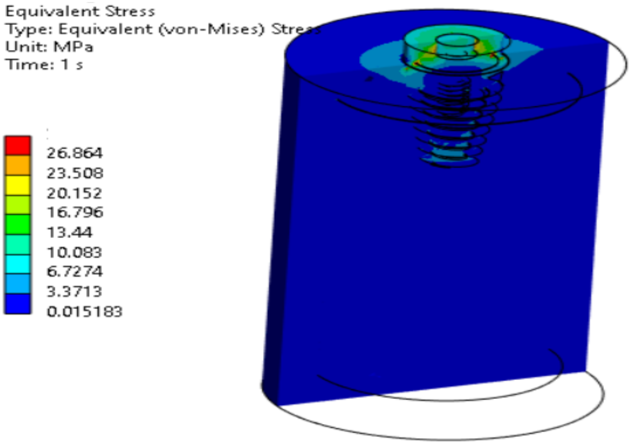


Fig 5: von Mises Stress Analysis

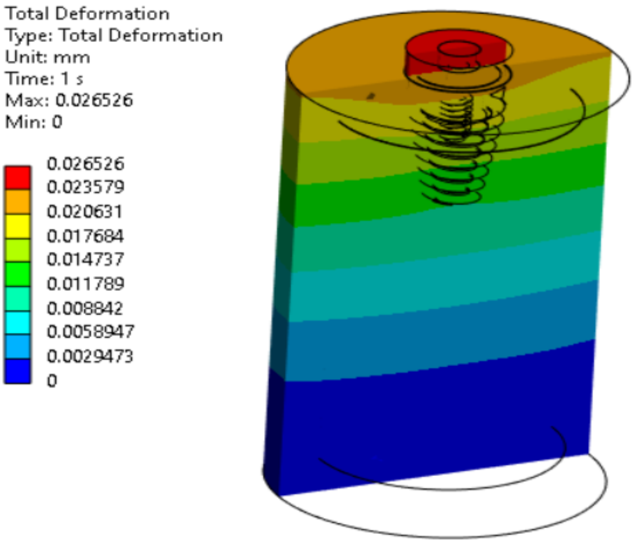


Fig 6: Micromotion analysis

Statistical Analysis

The collected data were compiled, tabulated and subjected to statistical analysis using the Statistical Package for the Social Sciences (SPSS) version 25.0, ensuring rigorous data interpretation and validation.The statistical tools used in the study included the mean, which was the average value of the observations and the standard deviation, which measured the amount of variation or dispersion in a set of values. The unpaired/independent t-test was employed to compare the means of two independent groups to determine if there was a significant difference between them. Additionally, the one-way ANOVA F-test was used to identify significant differences among multiple groups or variables under study, with a significance level of $p < 0.05$.

RESULTS

The von Mises stress analysis showed that in D_2 bone with platform-switched configurations, single-threaded implants (Group 1) exhibited the highest von Mises stress at 26.86 MPa. Double-threaded (Group 2) and triple-threaded (Group 3) implants showed reduced stress levels at 24.22 MPa and 24.33 MPa, respectively, while asymmetric implants (Group 4) had the lowest stress at 22.55 MPa. For regular platform configurations, single-threaded implants (Group 5) again showed the highest stress (26.75 MPa), whereas double-threaded implants (Group 6) exhibited the lowest stress (23.90 MPa). Triple-threaded (Group 7) and asymmetric (Group 8) designs had moderate stress levels at 24.90 MPa and 24.84 MPa, respectively.

In D_4 bone with platform-switched configurations, single-threaded implants (Group 1) showed the highest stress at 35.86 MPa. Double-threaded implants (Group 2) reduced stress to 29.88 MPa, and triple-threaded implants (Group 3) further reduced it to 24.33 MPa. Asymmetric implants (Group 4) had a stress level of 25.32 MPa. In regular platform configurations, single-threaded implants (Group 5) showed lower stress (33.37 MPa) than platform-switched equivalents. Double-threaded implants (Group 6) exhibited 31.6 MPa, while triple-threaded (Group 7) and asymmetric (Group 8) designs showed stress levels of 25.9 MPa and 28.5 MPa, respectively.

Whereas, micromotion analysis showed that in D_2 bone with platform-switched configurations, micromotion varied slightly among thread designs. Single-threaded implants (Group 1) showed the highest micromotion at 0.02652 mm, while double-threaded (Group 2) and asymmetric implants (Group 4) showed 0.02626 mm and 0.02607 mm, respectively. Triple-threaded implants (Group 3) had the lowest micromotion at 0.02593 mm. For regular platform configurations, single-threaded implants (Group 5) exhibited the highest micromotion (0.03915 mm), with double-threaded (Group 6), triple-threaded (Group 7), and asymmetric (Group 8) designs showing reduced micromotion at 0.03005 mm, 0.02948 mm, and 0.02905 mm, respectively.

In D_4 bone with platform-switched configurations, single-threaded implants (Group 1) had the highest micromotion at 0.02652 mm. Double-threaded (Group 2), triple-threaded (Group 3), and asymmetric (Group 4) designs exhibited 0.02642 mm, 0.02610 mm, and 0.02658 mm, respectively. For regular platform configurations, single-threaded implants (Group 5) showed 0.02975 mm, while double-threaded (Group 6), triple-threaded (Group 7), and asymmetric (Group 8) designs exhibited 0.03031 mm, 0.02973 mm, and 0.02976 mm, respectively.

In a comparative analysis of von Mises stress for D_2 bone, platform-switched designs resulted in a mean stress of 24.49 MPa, slightly lower than the regular platform's 25.10 MPa. Single-threaded implants showed the highest stress in both designs, while asymmetric designs exhibited the lowest stress in platform-switched configurations. The regular platform had less variability in stress (Fig. 7).

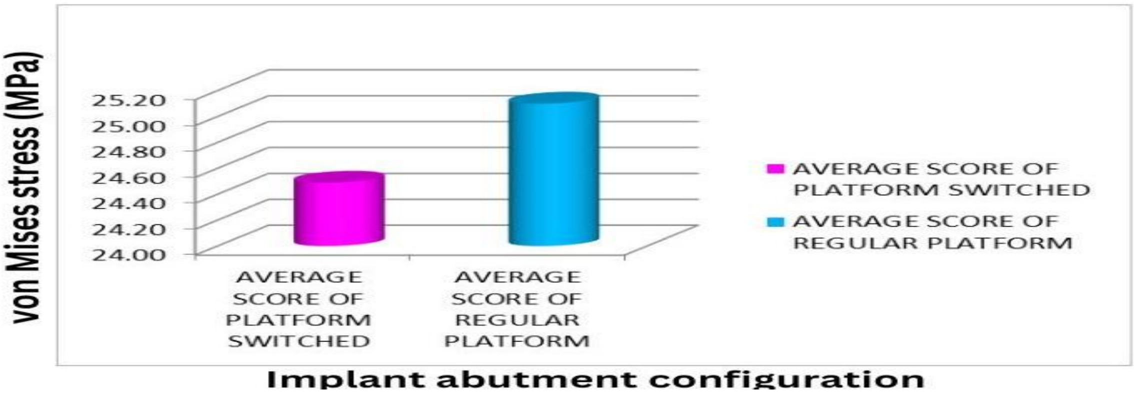


Fig 7: Analysis of von Mises Stress in D_2 bone with Platform Switched and Regular Platform implant abutment configurations.

In D_4 bone density, platform-switched configurations generally resulted in lower stress levels (28.85 MPa) compared to regular platforms (29.84 MPa). Single-threaded implants showed higher stresses, while triple-threaded and asymmetric designs exhibited lower stress levels in both configurations. The standard deviation was higher for platform-switched implants (Fig. 8).

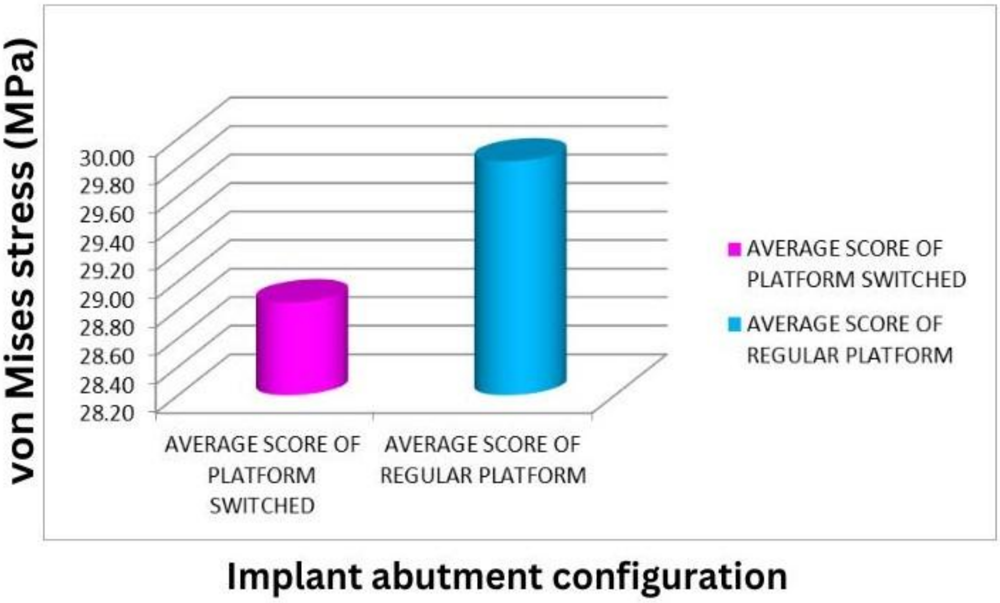


Fig 8: Analysis of von Mises Stress in D_4 bone with Platform Switched and Regular Platform implant abutment configurations.

In comparative analysis for micromotion for both D_2 and D_4 bone densities, platform-switched configurations resulted in marginally lower micromotion compared to regular platforms. The mean micromotion was consistently around 0.03 mm for both configurations, with minimal variations. Statistical tests indicated no significant differences in micromotion between D_2 and D_4 bone densities for either platform configuration(Fig. 9,10).

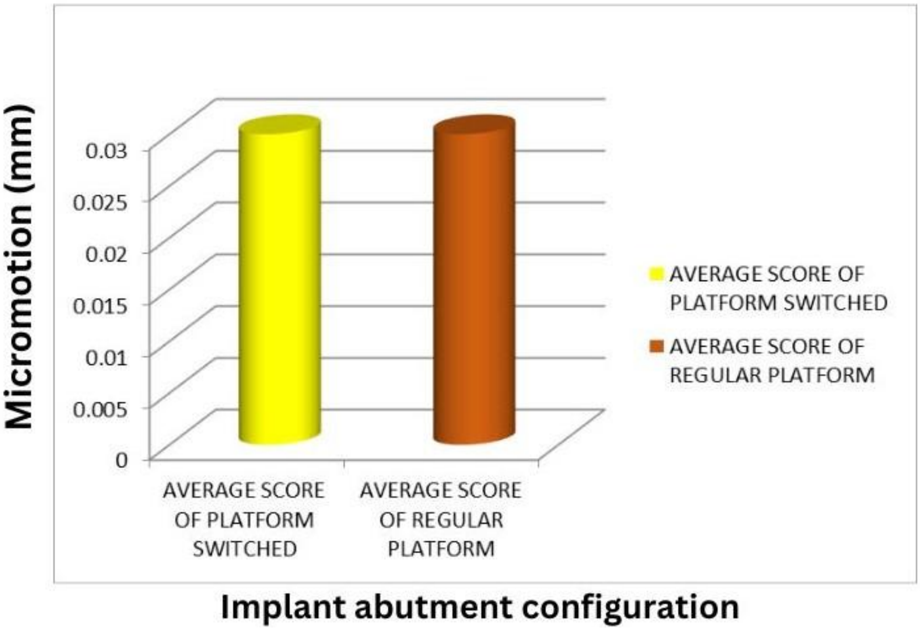


Fig 9: Analysis of micromotion in D_2 bone with Platform Switched and Regular Platform implant abutment configurations

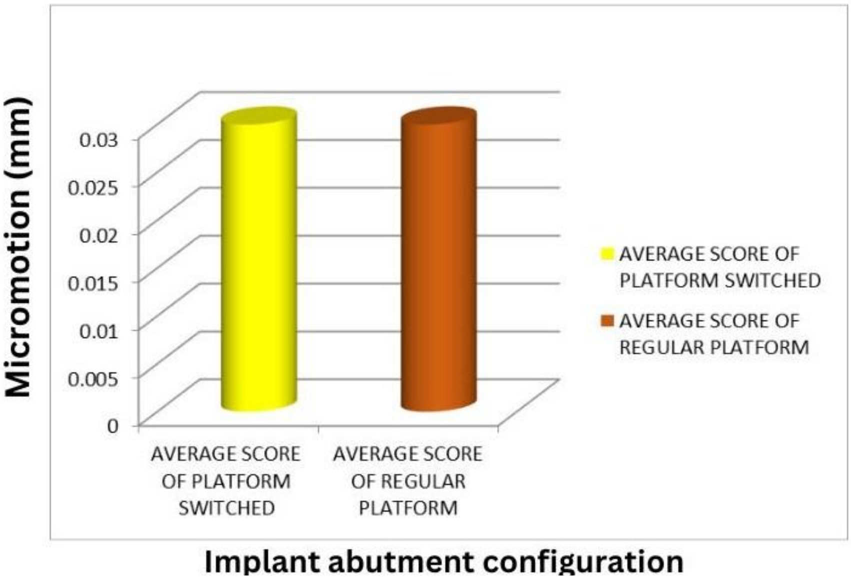


Fig 10: Analysis of micromotion in D_4 bone with Platform Switched and Regular Platform implant abutment configurations.

Overall, platform-switched configurations demonstrated slightly better performance in stress distribution and micromotion reduction across various thread designs, particularly in D_4 bone density. So, the null hypotheses were rejected as both thread design and platform configurations showed their effect on stress distribution and micromotion of the implant. However, the differences were not statistically significant in most cases, suggesting that both platform configurations could be viable depending on specific clinical scenarios.

Transitioning from D_4 to D_2 bone density, von Mises stresses in D_2 bone showed a 17.80% improvement for platform-switched implants and an 18.88% improvement for regular platform implants compared to D_4 bone density. In contrast, micromotion exhibited no percentage improvement between D_2 and D_4 bone densities for either platform-switched or regular platform implants.

DISCUSSION

Short dental implants, typically less than 8mm in length, offer a reliable alternative to bone augmentation procedures, particularly beneficial for patients with limited bone height or density.[11] They exhibit impressive survival rates, reaching up to 99.1% over an average follow-up of 3.2 ± 1.7 years, surpassing longer implants combined with bone augmentation.[12] Factors contributing to their success include bone density, patient habits, implant surface characteristics and prosthetic considerations. Wider implants provide greater contact area with surrounding bone, enhancing mechanical stability and promoting osseointegration.

To improve the performance of short implants, advancements in micro- and macro-designs have been introduced. These include changes in implant body shapes, innovative thread designs (e.g., variations in pitch or face angle) and enhancements in materials and surface coatings aimed at achieving long-term survival rates comparable to traditional implants.[13]

Platform-switched implant abutment configurations play a crucial role in preserving alveolar bone levels. This approach involves narrower abutments on wider implants, as opposed to matched abutment diameters. Studies, including those by Herekar et al., have shown that platform-switched configurations enhance bone preservation by increasing bone-implant contact. This effect is more pronounced with greater mismatches between implant and abutment diameters and when implants are placed subcrestally.[14]

The International Team for Oral Implantology (ITI) has introduced a one-step surgical technique for implants, allowing non-submerged implants and early loading. Ding X et al. in their study explained that immediate loading under optimal bone conditions has been associated with increased calcification levels and higher percentages of bone-implant contact. This approach is advantageous when bone density and volume are sufficient, and load expectations are moderate.[15]

According to a study by Şahin et al., various factors such as implant shape, length, diameter, angle, and placement within the dental arch, influence how forces are distributed on implants.[16] Vertical forces, typical during chewing, distribute evenly along the implant length and are generally well tolerated. In contrast, oblique forces can create uneven distributions and increase shear forces, potentially leading to implant failure over time as shown in a study by Cheng et al.[17]

Finite Element Analysis (FEA) serves as a valuable tool for studying implant biomechanics, offering insights into stress distribution and implant behavior under different loading conditions.[18] Advanced FEA techniques, incorporating nonlinear material properties and contact mechanics, improve the accuracy of implant models and help optimize implant designs to enhance stability and long-term success Furthermore, integrating FEA with advanced imaging modalities like cone beam computed tomography (CBCT) allows for precise patient-specific modeling and personalized treatment planning. This integration enhances the predictability and efficacy of implant therapy by optimizing implant placement and loading protocols based on individual anatomical data and material properties.[19]

Advancements in implant design, surgical techniques and biomechanical analysis through FEA continue to enhance our understanding and implementation of successful dental implant therapies. By optimizing these factors, clinicians can improve patient outcomes and minimize the risk of complications associated with implant procedures.

Accurate modeling of dental implants within the jawbone is crucial for understanding their complex behavior. This involves precise simulation of implant geometry, surface characteristics, and material properties of both the implant and surrounding bone, as well as the loading conditions they undergo. Finite Element Analysis (FEA) is a powerful tool that predicts how implants respond under different conditions, aiding in the assessment of factors like stress distribution and micromotion.

Brown et al. stated that nonaxial loading, which includes horizontal and oblique forces, can lead to complications such as marginal bone loss and implant failure. Understanding the stress thresholds that trigger biological responses like bone resorption requires both FEA data and clinical validation.[20]

FEA models can be either 2D or 3D, with 3D models offering more accurate results by capturing out-of-plane deformations and minimizing artificial constraints compared to 2D models. Recent studies such as by DeTolla DH et al., employing 3D FEA have evaluated how macro thread designs and platform configurations affect stress distribution and micromotion around short dental implants. These studies illustrate that 3D FEA provides a realistic approach to analyze dental implant biomechanics.[21]

Stress analysis using FEA, particularly through von Mises stress measurements, helps identify areas of potential weakness in implants. This criterion is essential for optimizing implant designs and materials to enhance durability and fatigue resistance. Similarly, micromotion studies using FEA are critical for assessing initial implant stability and osseointegration success, informing improvements in thread geometry and surface treatments to minimize micromotion and promote long-term implant performance.

Implant macro design, especially thread pitch, significantly impacts insertion speed and stability. Advances in manufacturing have introduced double and triple-threaded implants, accelerating the insertion process while maintaining stability, underscoring the importance of macro design in implantology. Asymmetrical thread designs further enhance stress distribution and bone adaptation, crucial for challenging anatomical conditions and compromised bone quality. Evaluating these designs using FEA ensures their biomechanical efficacy under various loading conditions.

Harris et al. stated that consideration of bone density in implant therapy is vital for optimizing implant outcomes and longevity. Clinicians choose implant designs and placement techniques based on bone density variations to enhance implant stability and minimize stress during functional activities. This comprehensive understanding of bone density's influence ensures successful dental implant therapy and patient satisfaction.[22]

In this study, von Mises stress and micromotion around immediately loaded short dental implants were examined under a 100N load applied at a 25^{o} buccolingual angle, comparing platform switched and regular platform implant abutments in both D_2 and D_4 bone densities. Controlling crestal bone loss is critical for long-term implant prognosis, ensuring vertical bone loss around implants remains minimal in the initial year and annually thereafter. The study found significant variations in von Mises stress among different thread designs across D_2 and D_4 bone densities with both platform configurations. Single-threaded designs exhibited the highest stress concentrations due to their limited load distribution, posing higher risks of micro-damage and implant failure under immediate loading conditions which was supported by studies conducted by Alqahtani A et al. and Ahn S et al.[23,24]

Platform-switched implant configurations showed lower stresses in cortical bone compared to regular platforms in both D_2 and D_4 bone densities, aligning with findings by Ferraz et al. indicating reduced stress and strain on the cortical plate with platform-switched configurations. This configuration distributes forces more evenly across the implant axis, mitigating concentrated stresses and maintaining biological width to protect against excessive bone stress.[25]

Regarding micromotion, triple-threaded and asymmetrical thread designs consistently exhibited lower values compared to single and double-threaded designs across both platform configurations and bone densities. This reflects the superior stability of complex thread geometries in reducing relative movement between the implant and bone, crucial for implant success under varying loading conditions.

Comparative analysis between D_2 and D_4 bone densities showed higher von Mises stresses in lower-density bone, consistent with findings that implants in denser bone experience less stress but may not always be statistically significant, emphasizing the role of implant design and placement techniques. Similarly, micromotion analysis revealed slightly less movement in platform-switched configurations, attributed to improved load distribution and reduced stress concentration at the bone-implant interface.

The study noted significant improvements in stress distribution efficiency with regular platform implants as bone density increased, underscoring the importance of implant configuration in adapting to varying bone densities, earlier by Natali et al. in their study.[26] However, no such enhancement was observed in micromotion with changes in bone density, highlighting the need for further investigation into dynamic loading and clinical validation.

The study had several limitations. Firstly, examining static loading scenarios, without exploring the potential effects of dynamic loading which are important in mimicking real-life conditions. Secondly, the bone models used in the finite element analysis (FEA) were assumed to be uniform and isotropic, which doesn't accurately reflect the heterogeneous and anisotropic nature of actual bone tissue. Thirdly, while oblique loading was considered to simulate realistic occlusal forces, future research should incorporate dynamic loading simulations to better understand the impact of chewing movements. Lastly, due to variations in bone quality, force distribution, and individual chewing habits, the findings of the study should be validated through randomized clinical trials for broader clinical applicability.

CONCLUSION

Within the limitations of this study, it can be concluded that:

1. Under immediate loading, implant thread designs and platform configurations impact stress distribution in peri-implant bone:
    - Single-threaded implants create higher von Mises stress in cortical bone compared to double, triple, and asymmetrical designs.
    - Platform-switched implants reduce cortical bone stress versus regular platform implants, with lower stress in D_2 than D_4 bone.
2. Implant thread designs and platform configurations affect micromotion in D_2 and D_4 bone densities:
    - Triple-threaded implants show minimal micromotion.
    - Platform-switched implants exhibit less micromotion than regular platform implants, though differences were not statistically significant.
    - Micromotion differences between D2 and D4 bone densities were not statistically significant for both platform configurations.
3. Platform-switched implants demonstrate significantly better von Mises stress distribution across different bone densities, improving by 17.80% from D_4 to D_2 bone, compared to an 18.88% improvement with regular platform implants.
4. Micromotion did not show significant differences between D_2 and D_4 bone densities for both platform types, suggesting bone density has minimal influence on micromotion in this context.

The study did not definitively establish the superiority of any specific implant design or platform configuration due to non-significant results. However, asymmetrical and triple-threaded designs with platform-switched configurations showed promising outcomes for stress distribution in both bone densities. Triple-threaded, platform-switched implants also exhibited lower micromotion, suggesting potential advantages under immediate loading conditions. Further research is needed to determine optimal configurations for minimizing peri-implant stress and micromotion across varying bone densities.

Author Contributions

Conceptualization: Dr. Roma Goswami; Data curation: Dr. Ayush Kumar; Formal analysis: Dr. Anshul Trivedi; Investigation: Dr.Ayush Kumar; Methodology: Dr. Ayush Kumar; Project administration: Dr. Roma Goswami; Validation: Dr. Anshul Trivedi; Visualization: Dr. Roma Goswami; Writing - original draft: Dr. Ayush Kumar; Writing - review & editing: Dr. Roma Goswami.

Conflicts of interest

There are no conflicts of interest.

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