Journal of Orthodontic and Periodontal Biomaterials Research

2025, Volume 5, Issue 2, Page No: 23-33

Galaxy Publication

Enhancing Orthodontic Mini-Implant Stability Through the Use of Stabilization Discs: An Experimental Investigation

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Received: 23 April 2025; **Revised:** 24 August 2025; **Accepted:** 06 September 2025

ABSTRACT

Orthodontic mini-implants often face challenges related to mobility and anchorage loss. The stabilization disc (SD), a flat device with four prongs made from biocompatible metals like titanium or stainless steel, has been developed to reinforce implant stability by distributing forces more evenly and reducing localized stress around the implant site. This study investigates how the inclusion of an SD affects the mechanical performance of mini-implants under orthodontic forces. A finite element model was constructed for a standard mini-implant (2.0 mm diameter, 12 mm length), and the mandible was reconstructed in three dimensions from CT images using SpaceClaim 2023.1. Orthodontic loading conditions were simulated by applying a 10 N force at a 30° angle. The study evaluated the impact of the SD on implant stability by measuring displacement, stress distribution, and cortical bone response, including von Mises stress and bone deformation. Mini-implants equipped with the SD showed a reduction in maximum displacement exceeding 41%, with stress more evenly spread across the implant and surrounding bone. Cortical bone deformation and stress levels were lower with the SD, indicating stronger anchorage and improved durability. The SD enhances mini-implant stability by mitigating stress concentrations and limiting deformation, all without permanent modifications to the implant. Its adaptability to different bone densities and capacity to withstand high orthodontic forces suggest it is a promising tool for improving anchorage in orthodontic treatment.

Keywords: Stress distribution, Mini-implant orthodontic, Finite element analysis, Stabilization disk, Orthodontic treatment

How to Cite This Article: Khalil MF, Al-Mutairi M, Enhancing Orthodontic Mini-Implant Stability Through the Use of Stabilization Discs: An Experimental Investigation. J Orthod Periodontal Biomater Res. 2025;5(2):23-33. https://doi.org/10.51847/GtQnp3NSj5

Introduction

Finite element analysis (FEA) has become an essential method in orthodontics, allowing detailed modeling of mini-implant mechanics under varying loading scenarios. By simulating factors such as stress patterns, insertion angles, and surface modifications, FEA aids in optimizing biomechanical forces, improving mini-implant stability, and reducing potential treatment complications [1-3]. This approach contributes to higher treatment success rates and better patient outcomes.

Orthodontic mini-implants are critical for providing reliable anchorage during treatment, and their mechanical responses under different conditions have been extensively explored. Sivamurthy and Sundari [1] investigated stress patterns around mini-implant sites, emphasizing how implant dimensions and loading directions affect computational outcomes. Similarly, Allum *et al.* [2] compared different implant sizes, showing how load variations influence bone response. Rito-Macedo *et al.* [3] further underlined the importance of evaluating peri-implant bone stress to guide implant design improvements.

Primary stability and effective stress distribution are key determinants of mini-implant success. The initial mechanical engagement of a mini-implant with surrounding bone, which depends on factors like bone quality, implant design, and insertion technique, largely dictates primary stability [4, 5]. Adequate primary stability is crucial for immediate loading, as any implant loosening can compromise treatment outcomes.

The mechanical characteristics of mini-implants—including geometry and surface properties—significantly influence stress distribution under orthodontic forces. Research shows that insertion angle, cortical bone thickness, and implant positioning can optimize load transfer, reducing stress and displacement and enhancing clinical success [6-8]. Surface treatments further improve stability by strengthening the mechanical interface between implant and bone [5, 9].

Mini-implant success rates are also affected by the magnitude and direction of applied forces, as well as clinician expertise [10, 11]. Reported failure rates range from 5% to 28%, highlighting the need for careful planning and precise placement [10]. Clinical studies, such as those by Shahanamol *et al.* [12], demonstrate practical advantages including immediate loading, versatile placement, and simplified procedures, complementing mathematical analyses by providing real-world validation and accounting for patient-centered factors like comfort and cost [12, 13].

Integrating computational modeling into implant design is essential to enhance performance and durability. Katić *et al.* [14] emphasize the influence of implant geometry on insertion torque, while Redžepagić-Vražalica *et al.* [15] compare different designs, underscoring the role of primary stability. Computational biomechanics also allows simultaneous evaluation of implant durability and kinematics [16]. Optimizing thread height and pitch has been shown to improve osseointegration and reduce bone stress [8]. FEA continues to be a valuable tool for analyzing cortical bone stress under loading conditions, as demonstrated by Choi *et al.* [17]. Future research should explore stress distribution during orthodontic movements such as retraction, intrusion, and molar uprighting [1], and assess primary stability across different implant materials to advance anchorage strategies [18].

The use of stabilization discs (SDs) in mini-implant systems further enhances primary stability and lowers failure risk by improving stress distribution and mechanical resistance. This study proposes that mini-implants fitted with SDs will outperform standard mini-implants in maintaining anchorage under orthodontic forces.

Materials and Methods

Ethical approval

The Research Ethics Committee of Grigore T. Popa University of Medicine and Pharmacy Iasi granted approval for this study (Approval No. 178/02.05.2022).

Patent status—Pending

The stabilization disc (SD) investigated here is an innovative service device currently in the patenting process. It has been formally submitted under the title "Disc de Stabilizare pentru Mini-Implantul Ortodontic" (Stabilization Disc for Orthodontic Mini-Implants) with application number 2024 00551 on 19 September 2024. The invention is scheduled for publication in the Official Bulletin of Industrial Property—Inventions Section No. 2 of 2025, in compliance with intellectual property regulations. Detailed descriptions, technical claims, and design specifications will be accessible to the public via OSIM starting 28 February 2025.

Three-Dimensional modeling and analysis

Three-dimensional representations of the mandibular implant sites and corresponding mini-implants were generated using Spaceclaim (version 19.2, ANSYS, Inc., Canonsburg, PA, USA). Subsequent finite element simulations were performed in ANSYS Workbench 19.2. The mandible model was derived from an STL-format optical scan to ensure anatomical fidelity and then streamlined to enhance computational performance and numerical stability during analysis **(Figure 1a)**.

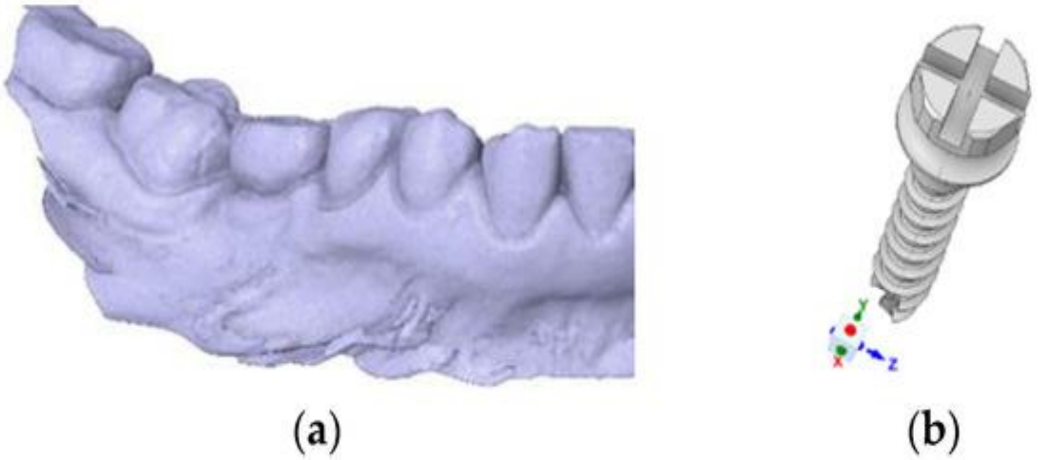


Figure 1. Finite Element Modeling Approach: (a) STL-format optical scan of the mandible; (b) STL-format CT scan of mini-implant model 1 and the corresponding CAD reconstruction produced in Spaceclaim

The mini-implant selected for analysis was modeled after commercially available designs from Dual Top Jeil Medical Corporation® (Seoul, South Korea) **(Figure 1b)**. The implant system was fabricated from Ti6Al4V titanium alloy. Its dimensions were 10 mm in length and 1.6 mm in diameter. **Figure 1b** illustrates the geometric representation of the implant system. The mini-implant's STL scan was used to construct a geometric model that preserved its actual dimensions, ensuring realistic simulation of stress distribution, displacement, and deformation. Finite element simulations were carried out in ANSYS to analyze these mechanical behaviors. The material characteristics applied in the simulations, including elastic modulus and Poisson's ratio, are summarized in **Table 1**.

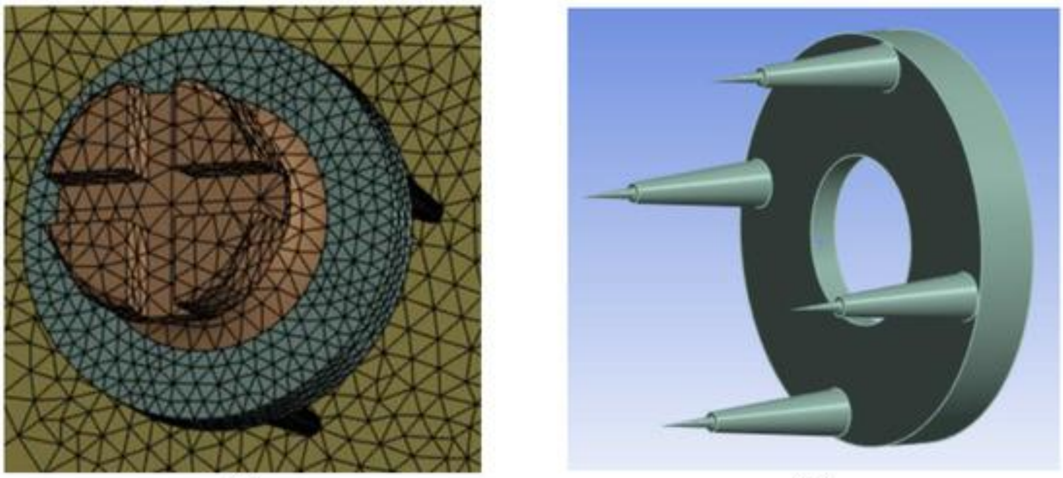
Table 1. The model of material properties used in the finite element analysis [19]

Material/Component	Elastic Modulus (MPa)	Poisson's Ratio
Cortical bone	17,000	0.3
Cancellous bone	350	0.25
Mini-implant	110,000/200,000	0.3
Bracket	380,000	0.19
Teeth	84,100	0.2
PDL	68.9	0.45

Structural analysis

Sd overview

A static structural analysis was performed under the assumption that the system is undamped and that material properties are uniform, ignoring any inhomogeneities. The device's stiffness was characterized using an elastic, isotropic material model. The SD, a medical innovation, is designed as a removable disc intended to address issues of mini-implant instability and unwanted movement during orthodontic procedures **(Figures 2a, 2b)**.



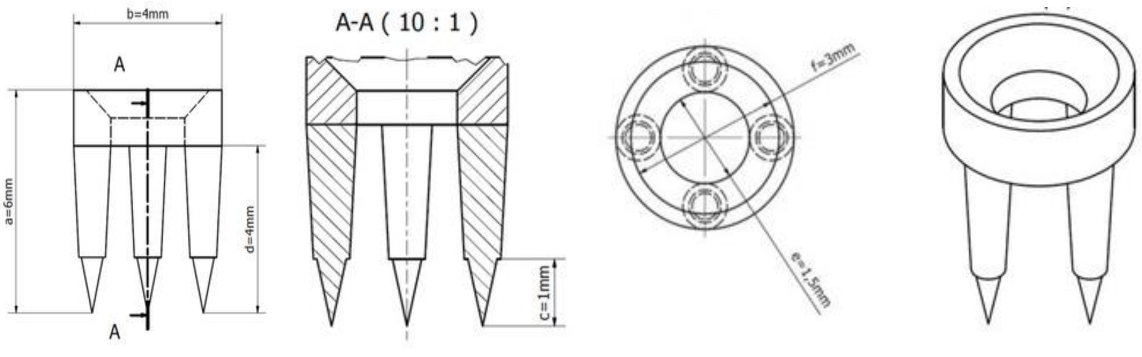
(a) (b)

Figure 2. Stabilization Disc (SD) Configuration: The disc is flat with a central opening precisely aligned to the diameter of the mini-implant's neck. Its smooth surface is crafted from Ti6Al4V alloy, the same material as the implant itself

Geometric characteristics of the stabilization disc (SD)
The SD has been engineered for precise and reliable placement within bone tissue, specifically for advanced orthodontic applications. Its dimensions and structure are optimized for performance:

Key measurements
The disc's outer ring measures 4 mm in diameter, with an internal opening of 1.5 mm and an external edge of 3 mm, ensuring proper fit with conventional mini-implants and maintaining mechanical stability. Each anchoring leg extends 4 mm into the bone, offering firm support while reducing strain on adjacent tissues. To prevent over-penetration of the cortical layer, the maximum insertion depth is capped at 1 mm, allowing controlled and safe positioning.

Design features
The SD is symmetrically constructed, with evenly spaced anchoring legs, as shown in the front **(Figure 3a)** and top **(Figure 3c)** views. This balanced design helps distribute applied forces evenly, minimizing localized stress points and enhancing the overall stability of the implant system.



a b c d

Figure 3. Detailed Representation of the SD: The illustration presents multiple views: (a) front elevation; (b) cross-section along line A–A; (c) plan view from above; (d) isometric perspective. Key dimensions are labeled as follows: ring height 6 mm (a), ring diameter 4 mm (b), maximum insertion depth 1 mm (c), leg height 4 mm (d), internal diameter 1.5 mm (e), and external diameter 3 mm (f)

The cross-sectional view **(Figure 3b)** reveals the precise tapering and spacing of the anchoring legs, optimized to facilitate insertion while providing enhanced stability once positioned. The isometric perspective **(Figure 3d)** conveys a complete three-dimensional understanding of the SD, showing how its components integrate to form a robust and precise device.

Simulation conditions

To replicate realistic orthodontic forces, a 10 N load was applied at a 30° angle relative to the vertical axis (Y-axis). This load was transmitted through the connector tube from the mini-implant to the molar, simulating the biomechanics of molar intrusion using skeletal anchorage. The angled force application accurately models clinical stress transfer, allowing detailed evaluation of stress and strain in the periodontal ligament, alveolar bone, and neighboring tissues.

Method validation and consistency

Reproducibility was ensured by consistently applying all geometric models, material parameters, and boundary constraints across simulations. The approach was validated against previously published studies, which reported comparable stress distributions and deformation patterns under similar conditions. Complete software settings and input parameters are available to enable replication.

Results and Discussion

Impact of the SD on mini-implant mechanics: Comparative findings

Equivalent von mises stress analysis

Stress distributions for both configurations are shown in **Figure 4a**. The highest stress, 80.682 MPa, was recorded for the mini-implant without the SD, whereas the configuration with the SD reduced the maximum stress to 41.613 MPa. The stress peak in the SD-supported scenario occurs closer to the surface, and the overall volume of material experiencing stress in both the bone and the implant is considerably lower, indicating more effective load management with the SD in place.

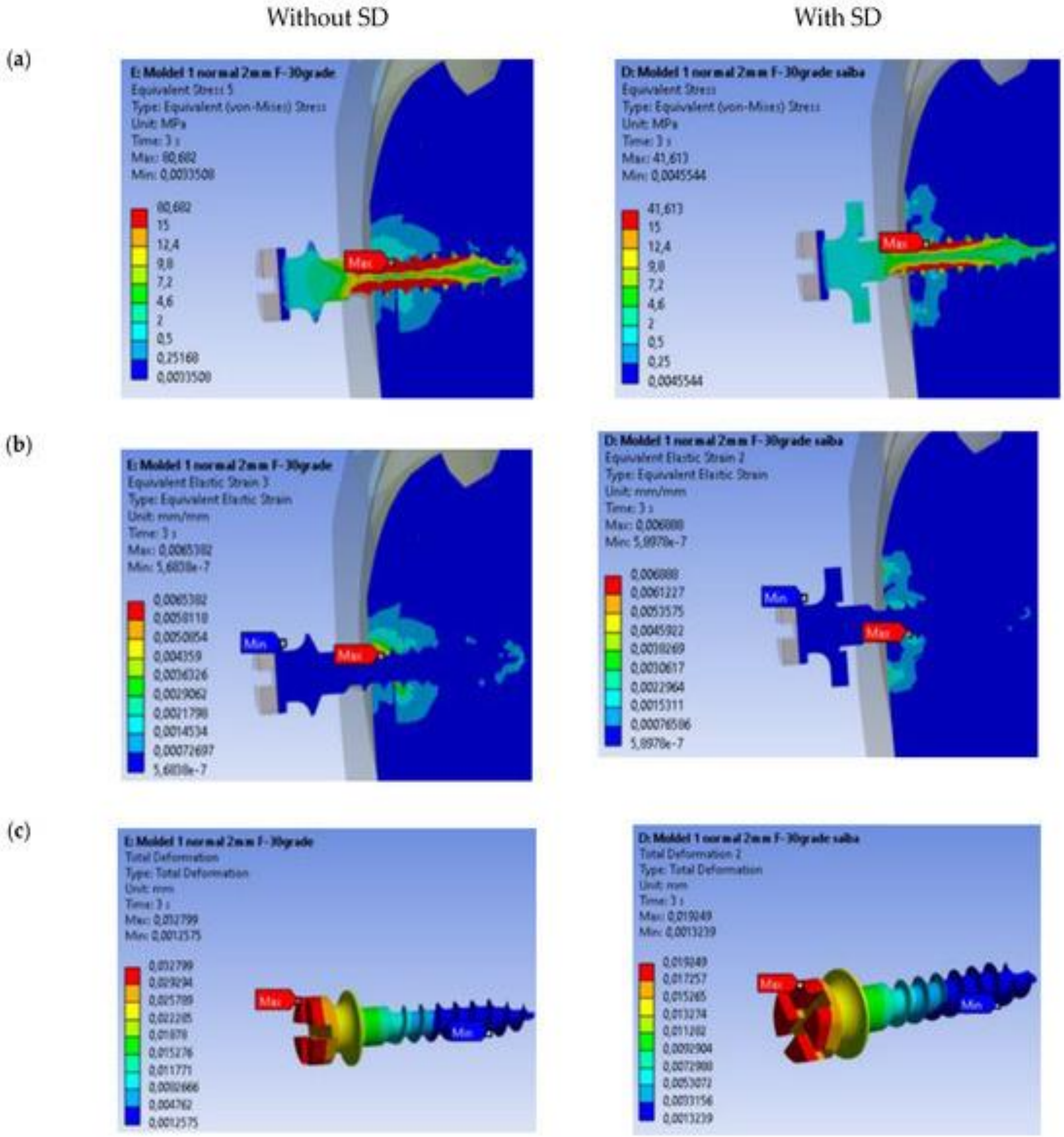


Figure 4. Comparative Evaluation: (a) Equivalent von Mises stresses; (b) linear equivalent strain distribution; (c) total deformation of the mini-implant, with and without the SD

Equivalent strain analysis

Figure 4b illustrates the linear equivalent strain distribution for the two configurations. The highest strain, 0.006888 mm/mm, occurs when the SD is incorporated. The strain patterns differ notably between the two cases, with peak values appearing at different locations and depths. Additionally, the overall volume of material experiencing strain is considerably smaller when the SD is in place.

Mini-Implant total deformation

Total deformation results under loading are shown in **Figure 4c**, comparing mini-implants with and without the SD. Without the SD, the maximum deformation reaches 0.032799 mm, with stress concentrations occurring at the implant–bone interface, reflecting reduced structural stability and uneven force distribution. When the SD is applied, the peak deformation is lowered to 0.019249 mm, demonstrating its effectiveness in dispersing mechanical forces more evenly and enhancing the rigidity of the system. These results clearly illustrate the functional benefits of incorporating an SD, as it lowers maximum deformation, reduces potential stress-related failures, and improves overall mechanical stability under orthodontic loading.

This analysis underscores the critical role of the SD in scenarios demanding high stability and minimal deformation. A comparative summary of the biomechanical performance of mini-implants with and without the SD is presented in **Table 2**, detailing key metrics such as von Mises stress, strain, and deformation.

Table 2. Comparative analysis of stress, strain, and deformation with and without the stabilization disc (SD)

Condition	von Mises Stress (MPa)	Strain	Deformation (mm)
	Maximum	**Minimum**	**Maximum**
Without SD	88.662	0.0032508	0.056063
With SD	41.613	0.0035544	0.050877

As illustrated in **Figures 5a, 5b**, the SD demonstrates a marked improvement in all evaluated aspects, including stress distribution, peak stress levels, linear strain, total deformation, and overall structural stability.

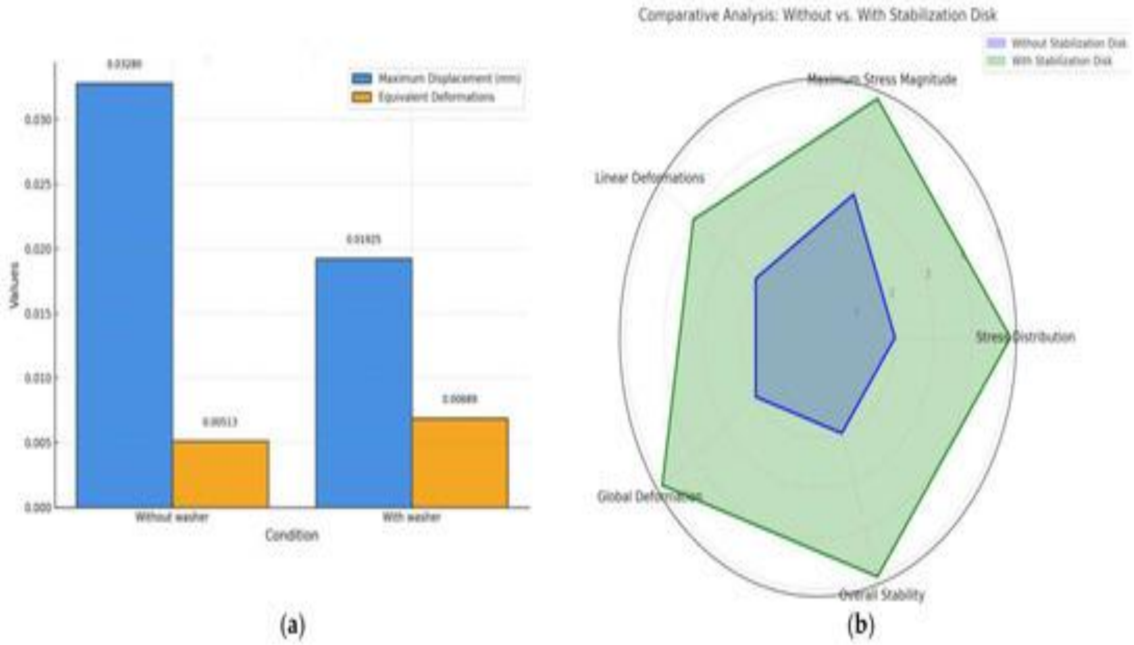


Figure 5. Effect of the SD: (a) Comparison of maximum displacement and equivalent strain in mini-implants with and without the SD; (b) spider chart illustrating mechanical performance differences between mini-implants with and without the SD

The use of stabilization discs and similar strategies to improve mini-implant stability has become an important focus in orthodontic research. Evidence suggests that multiple factors—including implant design and dimensions—play critical roles in maintaining stability. Lee *et al.* highlight that optimizing mini-implant geometry, thread design, and surface treatment can significantly enhance their performance under orthodontic loads [20]. Supporting this, Miglani and Cyan demonstrated that increasing implant diameter improves bone–implant contact, thereby boosting primary stability [21]. Sahoo further notes that mini-implants achieve superior bone-to-implant integration compared to conventional implants, which is essential for preserving stability during orthodontic procedures [22]. Seifi and Matini also observed that larger and longer mini-implants increase mechanical interlocking with bone, contributing to improved anchorage [23]. The importance of achieving mechanical stability is reinforced by Alsaeedi, who emphasizes that primary stability is crucial for orthodontic mini-implant success, as loosening can result in treatment failure [4].

Beyond design, insertion technique is a key determinant of stability. Chandak *et al.* explain that primary stability arises from the mechanical engagement of implant threads with the surrounding bone [24]. Popa *et al.* further highlight that self-drilling mini-implants enhance initial stability by maximizing bone contact, emphasizing the importance of insertion angle and technique [6]. Material selection also influences stability; for example, Pan *et* *al.* report that conical mini-implant designs can enhance primary stability, though excessive compressive stress during placement may introduce complications [25].

These findings suggest that innovations such as stabilization discs could further improve the mechanical interface and surface contact between mini-implants and bone, thereby enhancing overall stability. This is particularly relevant in regions with variable bone density, where both implant design and insertion approach must be carefully adapted to optimize anchorage [26].

Stabilization discs offer a versatile and non-permanent solution for augmenting mini-implant stability. Unlike modifications to implant shape, thread design, or surface treatment [20], which require changes during manufacturing, SDs can be applied selectively by the clinician based on treatment requirements or patient-specific anatomy. By increasing the contact area with cortical bone, SDs improve mechanical interlocking, which is especially advantageous in areas with reduced bone quality or density. For example, in regions like the posterior maxilla, SDs can distribute forces more evenly and decrease localized stress concentrations, as reflected in this study's findings by the reduced von Mises stress values.

The reduction in von Mises stresses has significant clinical implications for the longevity and reliability of mini-implants. Von Mises stress serves as a key indicator of mechanical stability, reflecting how forces are distributed through the surrounding bone. Stress distribution is also influenced by implant dimensions, indicating that both length and diameter are critical factors in managing biomechanical loads during orthodontic treatment [1].

Reducing von Mises stresses has a direct impact on the functional lifespan of orthodontic mini-implants, as lower stress levels help prevent bone necrosis and decrease the likelihood of implant failure. Excessive stress can cause microfractures and impaired blood flow in surrounding bone, delaying healing and jeopardizing implant stability [25]. Pan *et al.* have shown that high compressive forces at the bone–implant interface can negatively affect implant performance, underscoring the need for careful stress management [25]. Likewise, Sarika *et al.* highlighted that concentrated stress regions increase the risk of mini-implant failure, emphasizing the importance of precise insertion angles to minimize these hazards [27].

The data in **Figures 4a and 5a** demonstrate that the addition of the SD reduces the maximum total displacement of the mini-implant by approximately 41.3% (from 0.03280 mm to 0.01925 mm), indicating improved stability under orthodontic loading. Without the SD, the mini-implant exhibits greater movement, reflecting lower system rigidity.

Figures 4b and 5b show a similar trend for stress reduction: peak von Mises stress decreases from 80.682 MPa without the SD to 41.613 MPa with the SD, nearly a 48.5% reduction. The stress is also distributed more evenly, and the volume of high-stress material is smaller for both the implant and surrounding bone.

Previous studies provide additional context for these findings. Sivamurthy and Sundari reported stress values ranging from 19.85 MPa to 43.34 MPa for mini-implants measuring 1.3 × 6 mm and 1.3 × 8 mm under retraction and intrusion, which are within titanium's fatigue limit [1]. Zhou *et al.* observed that loading stresses are primarily concentrated in cortical bone near the implant neck, indicating that implant design and positioning are critical for stress management and reducing failure risk [8]. These results suggest that the SD not only extends implant longevity but also minimizes the risk of bone damage during treatment. Additionally, in the presence of the SD, peak stress in cortical bone occurs deeper within the tissue, where bone can better tolerate mechanical load, further contributing to enhanced stability. Regarding equivalent specific deformations **(Figures 4c and 5a)**, the SD significantly lowers the affected volume, even though the maximum deformation is similar, demonstrating its role in distributing forces more evenly and minimizing overall deformation.

The SD developed for orthodontic anchorage **(Figures 2 and 3)** is a flat, four-pronged disc constructed from biocompatible materials such as titanium or stainless steel, depending on the mini-implant composition. Key dimensions include: ring height 6 mm, ring diameter 4 mm, maximum bone insertion 1 mm, leg height 4 mm, internal diameter 1.5 mm, and external diameter 3 mm. Each prong has a flat surface to secure the disc in place and maintain stability during treatment.

Positioned between the mini-implant tip and surrounding bone or gingival tissues, the SD serves as an auxiliary support structure, enhancing mechanical interlock and force distribution. By inserting the disc, clinicians can reduce localized stress and displacement, lowering the risk of implant loosening or detachment. This additional support improves overall anchorage reliability, ensuring consistent implant performance throughout orthodontic procedures. The SD effectively addresses common challenges in clinical practice by preventing mini-implant mobilization and providing a more even distribution of forces at the insertion site, thereby enhancing structural stability and treatment efficacy.

This design helps prevent mini-implant mobilization or loosening during orthodontic procedures, thereby providing more consistent and reliable anchorage for treatment. The influence of SDs on stress distribution within cortical and cancellous bone is a critical area of investigation, particularly for mini-implants employed as orthodontic anchorage. By modifying how forces are transmitted through the surrounding bone, SDs can substantially affect implant stability and the structural integrity of adjacent bone tissue, ultimately impacting overall treatment outcomes.

Mini-implants placed in regions such as the infrazygomatic crest (IZC) and mandibular buccal shelf (MBS) have transformed orthodontic practice by offering stable anchorage, reducing the risk of root injury, and enabling precise control of tooth movement in three dimensions [28]. Their ability to simultaneously manage roll, pitch, and yaw has greatly improved treatment results, particularly in complex malocclusions where conventional methods are insufficient. Nevertheless, the biomechanical performance of these systems remains constrained by anatomical and physiological factors [29, 30]. The incorporation of stabilization discs into mini-implant setups presents a promising solution to these limitations, enhancing clinical stability and functional outcomes. Future research exploring long-term stability and optimizing biomechanical applications will be essential to further expand the utility of mini-implants in contemporary orthodontics.

Limitations of the study

(a) Simplified Modeling: The experimental design relied on simplified geometric and biomechanical models that may not fully capture the complexity of clinical conditions. For example, interactions between different tissues, such as soft tissue and bone interfaces, were not comprehensively represented. Future studies should implement more anatomically and biomechanically realistic models to enhance clinical relevance.

(b) In Vitro Conditions: Conducting the study in vitro limits its applicability to actual clinical scenarios. Unlike in vivo environments, where factors such as bone remodeling, soft tissue dynamics, and patient-specific variability occur, the controlled laboratory setting does not account for these interactions, potentially leading to over- or underestimation of the SD's performance.

(c) Finite Element Analysis (FEA) Assumptions: While FEA is a robust tool for mechanical evaluation, its accuracy is constrained by the assumptions and simplifications made during model construction. For instance, the study assumed isotropic and homogeneous material properties, which may not accurately reflect the anisotropic and heterogeneous nature of bone or the complex interactions in the biomechanical system.

(d) Idealized Material Properties: The simulations used uniform material properties for all components, assuming consistency and homogeneity. In clinical practice, variations due to manufacturing tolerances, material aging, or patient-specific factors could affect the behavior and performance of both the mini-implant and the SD.

(e) Focus on a Single Variable: This study primarily evaluated the impact of the SD on mini-implant stability without considering other influential factors such as patient-specific characteristics (e.g., bone density, age, systemic health) or alternative treatment protocols. Including these variables in future analyses would provide a more comprehensive understanding of treatment outcomes.

(f) Short-Term Assessment: The study examined only the short-term mechanical behavior of the system under simulated conditions. Long-term performance, including implant stability over months or years and potential complications such as bone resorption or implant failure, was not assessed, limiting insight into the SD's durability.

(g) Proximity to Teeth and Soft Tissue Risk: Although the SD improves anchorage stability, its placement near teeth or in areas with limited interproximal space may pose challenges. Close proximity to adjacent teeth increases the risk of inadvertent contact or interference during insertion. Additionally, sharp prongs on the SD could potentially damage soft tissues, especially in areas with thin gingiva. Future work should evaluate safety and efficacy in these anatomical contexts.

(h) Absence of In Vivo Validation: While FEA provided valuable mechanical insights, the lack of in vivo testing represents a key limitation. Factors such as bone remodeling, tissue responses to load, osseointegration, and anatomical variability are not captured in this study, which may limit the direct applicability of findings to clinical orthodontic practice.

(i) Bone Adaptation: The study does not account for biological processes such as bone remodeling or healing that occur following mini-implant placement and loading, which could modify stress distributions over time.
(j) Force Variability: The simulations applied static forces, which do not replicate the dynamic and variable forces experienced in actual orthodontic treatment.
Individual patient characteristics, including variations in bone density, cortical thickness, and overall biomechanical differences, were not accounted for in the standardized model used.

Conclusion

Incorporating stabilization discs into mini-implant systems offers a significant improvement in orthodontic practice, enhancing mechanical stability, optimizing stress distribution, and minimizing deformation during treatment. This adaptable solution effectively addresses challenges such as variations in bone density and the application of high orthodontic forces, all without requiring permanent alterations to the implant's original design.

Acknowledgments: None

Conflict of interest: None

Financial support: None

Ethics statement: None

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