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ORIGINAL ARTICLE

A novel dental implant nut system designed to enhance primary stability: Mechanical and finite element analysis

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Abstract

Purpose: The present study aimed to evaluate, in a preclinical setting, the biomechanical behavior and mechanical performance of a newly developed dental implant nut system designed to address primary stability challenges in the severely resorbed posterior maxilla.

Materials and Methods: The evaluation consisted of two complementary stages: an in vitro mechanical experiment and a finite element analysis (FEA). In the experimental phase, polyurethane jaw models simulating a severely atrophic posterior maxilla with approximately 1 mm residual bone height were used. Four groups were prepared: single implant without nut, single implant with nut, double implant without nut, and double implant with nut ($n = 10$ per group). Primary stability was measured using resonance frequency analysis (RFA) with an Osstell device. In the computational phase, three-dimensional finite element models were constructed from cone-beam computed tomography (CBCT) data of the same configuration to evaluate detachment forces and stress distribution within the bone–implant complex under vertical loading.

Results: In single-implant models, mean implant stability quotient (ISQ) values increased from 10.91 ± 7.35 to 18.27 ± 7.11 after nut application. In double-implant models, ISQ values increased from 11.13 ± 4.14 to 19.24 ± 4.24 ($p < 0.05$). FEA results revealed that the detachment force increased from 16.5 to 20.33 N in single-implant models and from 15 to 22.3 N in double-implant models. Compressive stresses on the bone were lower in nut-supported configurations, indicating a more favorable load distribution.

Conclusion: The nut system was associated with increased implant primary stability and a more favorable stress distribution under the conditions of this preclinical study. These findings should be interpreted as preliminary biomechanical evidence, as no in vivo or clinical validation was performed. Therefore, this design may be considered a mechanical stabilization concept that warrants further investigation through in vivo and clinical studies.

KEYWORDS
biomechanics, dental implants, finite element analysis, implant nut system, posterior maxilla, primary stability

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With increasing life expectancy, the need for functional and aesthetic rehabilitation of missing teeth has been steadily rising. Accordingly, owing to their high biocompatibility, reliable osseointegration, and long-term success rates, dental implants are currently regarded as the most reliable and "gold standard" approach in oral rehabilitation.[1, 2] The primary stability of a dental implant plays a crucial role in the success of osseointegration. This mechanical stability, achieved at the time of placement, is primarily influenced by local bone quality and quantity, implant design, and the surgical placement technique.[3, 4] Misch classified bone according to its density and trabecular characteristics, defining D3 bone as thin cortical with trabecular structure and D4 bone as weak cortical with loose trabecular pattern. Since the posterior maxilla predominantly exhibits D4-type bone characteristics, achieving primary stability in this region is more challenging compared to other areas.[5] Furthermore, following tooth extraction, the alveolar bone undergoes progressive resorptive changes, resulting in a noticeable reduction in bone volume—most prominently in the posterior maxilla, where both residual ridge resorption and sinus pneumatization occur concurrently.[6] This region, characterized by the lowest residual bone height, presents significant surgical challenges for implant-supported rehabilitation.[7]

Over time, several bone augmentation techniques have been developed to address this issue. Among these, sinus lifting procedures—where autogenous bone grafts are combined with various types of allografts and biomaterials—represent one of the most commonly used approaches.[8] Grafting techniques based on the elevation of the maxillary sinus floor are still considered among the most predictable and cost-effective methods for overcoming these anatomical limitations.[9] Depending on the residual bone height and the level of primary stability that can be achieved, implant placement may be performed simultaneously with sinus surgery in a single-stage approach or, after a certain healing period, through a delayed two-stage protocol. If the remaining alveolar bone height allows for sufficient primary implant stability, dental implants can be placed simultaneously with the augmentation procedure; however, when adequate stability cannot be achieved, implant placement may be delayed and performed at a later stage.[10]

Various methods have been used to evaluate implant stability. The resonance frequency analysis (RFA) technique, originally described in 1996, measures the stiffness of the implant–bone interface in a noninvasive manner, and the resulting implant stability quotient (ISQ) values are expressed on a scale from 1 to 100.[11] However, in vivo measurements can be influenced by variations in bone density, cortical thickness, and anatomy. Therefore, polyurethane models that mimic the mechanical properties of natural bone are widely used as reliable, standardized, and reproducible materials for biomechanical testing.[12] Mechanical tests on polyurethane models and RFA measurements provide reliable and reproducible data for evaluating implant stability. However, these methods primarily assess macroscopic stability and do not allow detailed analysis of the biomechanical contact, stress distribution, or load transfer at the implant–bone interface. Therefore, the finite element stress analysis (FEA) method is employed as a noninvasive complementary tool to analyze the mechanical behavior, stress, and strain distributions of different geometries, including the implant and surrounding bone, under physiological conditions.[13, 14] In the severely atrophic posterior maxilla, various techniques have been developed by different researchers to enable simultaneous implant placement with the sinus lift procedure.[2, 15–17] Although each technique has its own advantages and disadvantages, most approaches entail limitations such as surgical complexity and additional cost.

In the present study, to explore a potential approach to this clinical challenge, the biomechanical behavior and primary stability of a newly developed dental implant nut system were evaluated in a preclinical setting using mechanical testing on polyurethane jaw models and finite element analysis (FEA).

MATERIALS AND METHODS

The present study was approved by the Dean's Office of the Faculty of Dentistry, Erciyes University (Decision No: 607430, dated February 20 2024). It was conducted collaboratively at two research centers to ensure methodological rigor and reproducibility. The polyurethane model experiments were performed at the Department of Oral and Maxillofacial Surgery, Faculty of Dentistry, Erciyes University (Kayseri, Türkiye), while the FEAs were carried out at the Department of Mechanical Engineering, Faculty of Engineering, Abdullah Gül University (Kayseri, Türkiye).

Design of the implant and nut system

The nut system used in this study was manufactured from the same raw material as the implant, namely, Grade 4 titanium. The threads of the nut were designed to be fully compatible with those of the implant, and the production was carried out accordingly. The lower portion of the nut contained four anchoring tines designed to enhance bone engagement and mechanical locking. These tines were sharply pointed and configured to penetrate the bone when rotated clockwise.

To prevent accidental displacement of the system into the maxillary sinus during application, a 0.8-mm diameter safety hole was created on the nut. During the surgical procedure, a wire or suture thread could be passed through this hole to prevent the device from accidentally falling into the sinus cavity. The basal surface of the nut, which comes into contact with the sinus floor, was designed with narrowed buccopalatal sides to ensure better adaptation to narrow sinus floor configurations. Additionally, a knurled surface was added to the upper portion of the nut to improve grip and control of hand instruments during transport and placement. At the interface between the implant and the nut, a chamfered seating surface was incorporated to allow the implant to fit smoothly into the nut housing and to ensure precise thread engagement. This

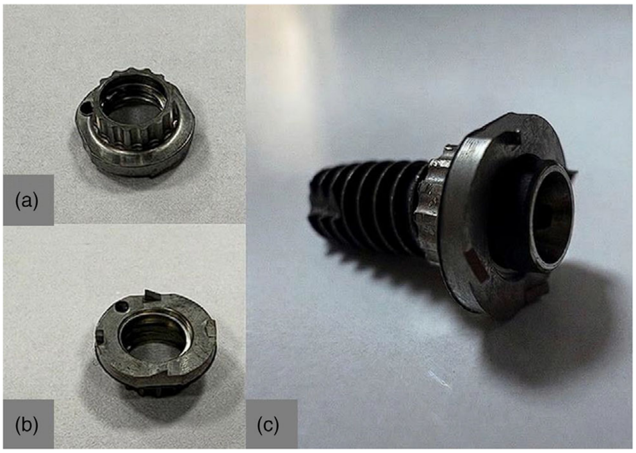

FIGURE 1 General view of the custom-designed implant nut system used in this study: (a) top view of the dental nut, (b) bottom view of the dental nut, and (c) assembled view of the implant and nut system.

design provides stable implant positioning within the nut and maintains the overall mechanical integrity of the connection (Figure 1).

Polyurethane model design and experimental grouping

The average bone density in the posterior maxilla is approximately 0.31 g/cm^3.[18] Accordingly, in the present study, polyurethane models (Selbone) with a density of 20 pcf (pound per cubic foot) and an approximate residual bone height of 1 mm were used. These models were designed to simulate severely atrophic maxillary conditions and to represent single-tooth edentulous sites (region #16) and two-tooth edentulous sites (regions #26–27).

A total of four experimental groups were created, each consisting of 10 models. Group 1: single implant, Group 2: single implant with nut, Group 3: two implants, and Group 4: two implants with nuts. In Groups 3 and 4, each implant site was defined separately for clarity and consistency. In this naming system, the letter "A" represents the implant in region #26, while the letter "B" represents the implant in region #27. The experimental groups and subgroup definitions are summarized in Table 1.

Implant placement and measurement protocol

In Groups 1 and 3, 10 and 20 implants, respectively, were placed. In both groups, titanium implants measuring 4.1 mm in diameter and 10 mm in length (Bilimplant; Proimtech Inc.) were inserted following the manufacturer's standard drilling protocol (Figure 2a).

In Groups 2 and 4, 10 and 20 implants, along with an equal number of nut components, were used. In these groups, a lateral sinus window was first prepared on the models. After completing the standard drilling sequence, the nut component was guided through the sinus window using a needle holder (porte-aiguille) and mechanically locked onto the sinus floor via its claw-like extensions. Subsequently, the implants were inserted into their osteotomy sites and securely engaged with the nut system (Figure 2b,c).

TABLE 1 Experimental groups and configurations.

Group	Region(s)	Model type	Nut system	Notation
Group 1	#16	Single-tooth edentulous model	Absent	–
Group 2	#16	Single-tooth edentulous model	Present	–
Group 3A	#26	Two-tooth edentulous model	Absent	A = #26
Group 3B	#27	Two-tooth edentulous model	Absent	B = #27
Group 4A	#26	Two-tooth edentulous model	Present	A = #26
Group 4B	#27	Two-tooth edentulous model	Present	B = #27

Note: Groups 1 and 2 represent single-tooth edentulous models, whereas Groups 3 and 4 represent two-tooth edentulous models.

After implant placement, RFA was performed using the Osstell ISQ device (Osstell AB) with a SmartPeg Type 32. Measurements were taken perpendicular to the implant axis from the buccal, palatal, mesial, and distal surfaces, and each was repeated three times to calculate the mean ISQ value for each implant (Figure 3a,b). Finally, Groups 1–2 and 3–4 were compared to evaluate the effect of the nut system on implant primary stability, based on ISQ values obtained.

Statistical analysis

The sample size was determined based on the RFA data reported by Mello et al.[19] for dual-cone implants in the buccolingual (BL) and mesiodistal (MD) orientations. Using G*Power 3.1 software (Heinrich Heine University), a power analysis was performed considering an effect size (d = 3.925), a significance level (α = 0.05), and a statistical power ($1-\beta$ = 0.95), indicating that at least four samples per group were required. To enhance statistical reliability, 10 polyurethane models were included in each group. Accordingly, 10 implants were placed in each of Groups 1 and 2, and 20 implants were placed in each of Groups 3 and 4.

Statistical analyses were performed using IBM SPSS Statistics 26.0 software (IBM Corp.). Data distribution was assessed using skewness and kurtosis values, and since all variables were within the range of −2 to +2, the data were assumed to follow a normal distribution. Comparisons between independent groups were conducted using the independent samples t-test, and statistical significance was set at $p < 0.05$.

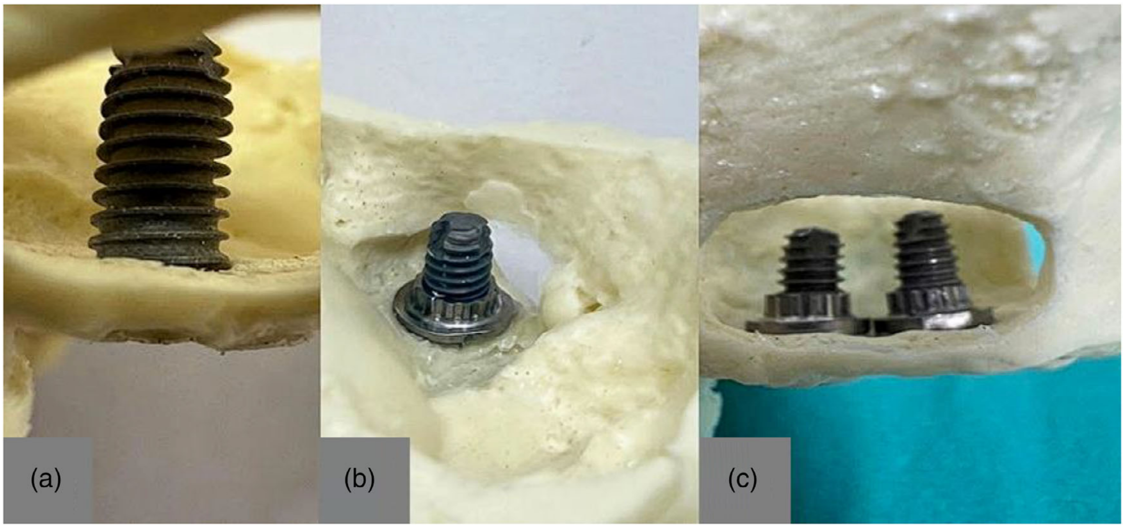

FIGURE 2 Implant and nut system placement configurations: (a) Single-implant placement without the nut system. (b) Single-implant placement with the nut system locked to the sinus floor. (c) Dual-implant configuration with the nut system applied to both implants.

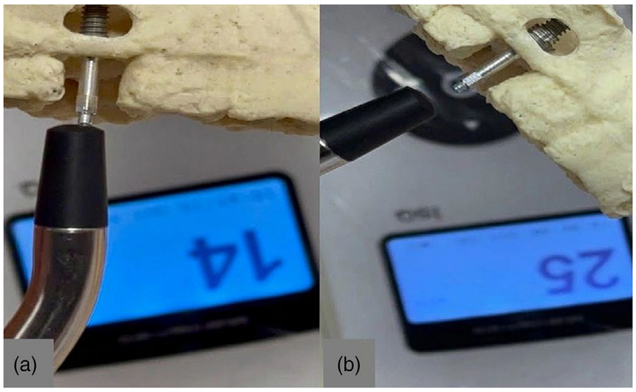

FIGURE 3 Resonance frequency analysis (RFA) measurement setup in single-implant models: (a) RFA measurement performed on a nut-free implant using the Osstell ISQ device and SmartPeg Type 32. (b) RFA measurement performed on a nut-assisted implant after mechanical locking of the nut system. ISQ, implant stability quotient.

Finite element analysis

Modeling

Three-dimensional (3D) models of a severely atrophic posterior maxilla (1 mm residual bone height) were created from Digital Imaging and Communications in Medicine (DICOM) data obtained from the polyurethane models using Materialise Mimics v24.0 (Materialise NV). The bone, implant, healing abutment, and nut system geometries were refined in Autodesk Fusion 360 (Autodesk Inc.) and assembled in SolidWorks 2021 (Dassault Systèmes) to replicate the clinical anatomy.

Four models were generated to represent different clinical scenarios:

Model 1 (M1) represented a single-tooth edentulous site with an implant placed without a nut.
Model 2 (M2) represented a single-tooth edentulous site with an implant placed using a nut.
Model 3 (M3) represented a two-tooth edentulous site with two implants placed without nuts.
Model 4 (M4) represented a two-tooth edentulous site with two implants placed using nuts.

Assembly and material properties

All models were imported into ANSYS Workbench 2022 R2 (ANSYS Inc.) in STEP format. Surface repairs were performed in SpaceClaim (ANSYS Inc.), and watertight geometries were prepared for meshing (Figure 4a).

All materials were assumed linear, homogeneous, and isotropic. The elastic modulus (E) and Poisson's ratio (ν) were assigned as follows: Titanium Grade 4 (implants, nut, healing abutment): $E = 110$ GPa and $\nu = 0.34$; cortical bone equivalent for the atrophic maxilla: $E = 1.37$ GPa and $\nu = 0.30$. Trabecular bone was not modeled separately; instead, a cortical bone equivalent was used to simulate advanced atrophic conditions.

Interface conditions

The contact definitions were established as follows: implant–bone, nut–bone, and implant–nut interfaces were defined as frictional contacts with a coefficient of friction (μ) of 0.30; the healing abutment–implant interface was modeled as bonded with no relative motion. Contact regions were automatically generated and manually refined where necessary (Figure 4b,c).

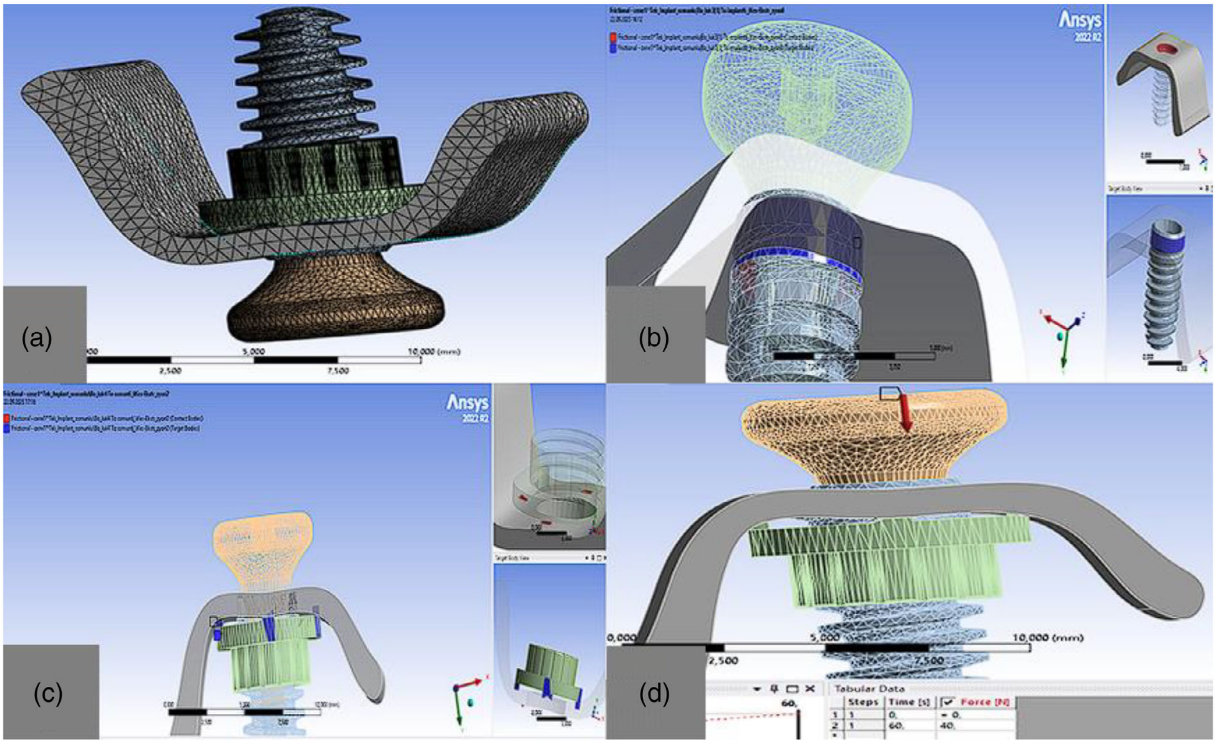

FIGURE 4 Finite element model preparation and loading scheme. (a) Finite element mesh view of the nut-assisted single-implant model (M2). (b) Frictional contact interface between the implant and the surrounding bone (implant–bone contact). (c) Frictional contact interface between the nut component and the surrounding bone (nut–bone contact). Other frictional contacts, such as the implant–nut interface, were defined similarly but are not shown for clarity. (d) Application of vertical occlusal loading in the finite element model.

Loading and boundary conditions

The lower and lateral surfaces of the maxillary segment were fully constrained in all directions. A vertical occlusal load was applied to the upper surface of the healing abutment, increasing linearly from 0 to 40 N over 60 s (Figure 4d). A sub-step control method (initial: 60, minimum: 40, maximum: 100) was applied to ensure numerical stability and convergence.

Analysis and evaluation

All models were tested under identical loading conditions to determine the force (N) and time (s) at which implants detached from the simulated bone. These values were used to quantitatively assess the additional primary stability provided by the nut system. To enable direct comparison between nut-assisted and nut-free models under equivalent mechanical conditions, the detachment force values measured in the nut-free models were applied to the nut-assisted models. This approach allowed evaluation of stress distributions and principal stress patterns within the cortical bone and demonstrated the influence of the nut system on load transfer and stress concentration. Identical boundary and loading conditions were maintained across all models to ensure consistent and reliable comparisons.

RESULTS

Mechanical test results on polyurethane models

The mean ISQ value in Group 2 was significantly higher than that in Group 1 (18.27 ± 7.11 vs. 10.91 ± 7.35; $p = 0.027$). Region-specific analysis revealed statistically significant differences at the buccal and palatal surfaces ($p = 0.037$ and 0.021, respectively), while the mesial and distal surfaces showed near-significant increases ($p = 0.063$ and 0.057, respectively). Overall, the use of the nut system consistently enhanced implant stability in all measurement directions, indicating a clear improvement in primary stability within single-tooth edentulous models. The comparative ISQ values for Groups 1 and 2 are summarized in Table 2.

The mean ISQ value in Group 4 was significantly higher than in Group 3 (19.24 ± 4.24 vs. 11.13 ± 4.14; $p < 0.001$). Region-specific analysis showed statistically significant differences in all measurement directions—buccal, palatal, mesial, and distal ($p < 0.001$). The comparative ISQ values for Groups 3 and 4 are presented in Table 3.

FEA Results

In M1, the nut-free implant detached from the simulated bone at 24.5 s under 16.5 N, whereas in M2, the nut-assisted

TABLE 2 Comparison of implant stability quotient (ISQ) values between nut-assisted and conventional implant placements.

Variables	Buccal	Palatal	Mesial	Distal	Mean ISQ
Group 1	11.64 ± 8.00	10.45 ± 8.23	11.27 ± 7.67	10.27 ± 8.22	10.91 ± 7.35
Group 2	19.45 ± 8.39	19.18 ± 8.17	17.36 ± 6.83	17.09 ± 7.60	18.27 ± 7.11
t	−2.236	−2.496	−1.967	−2.020	−2.388
p	0.037*	0.021*	0.063	0.057	0.027*

Note: Values are presented as mean ± standard deviation. Group 1 represents implants placed without the nut system, while Group 2 represents implants placed with the nut system. Comparisons were performed using independent samples *t*-tests. The *t* values represent the test statistics. Negative *t* values indicate higher means in the nut-assisted group.
*$p < 0.05$ was considered statistically significant.

TABLE 3 Comparison of implant stability quotient (ISQ) values between nut-assisted and conventional implant placements in two-tooth edentulous models.

Variables	Buccal	Palatal	Mesial	Distal	Mean ISQ
Group 3	12.95 ± 4.48	8.80 ± 5.63	10.80 ± 5.17	11.95 ± 5.52	11.13 ± 4.14
Group 4	20.15 ± 7.18	17.55 ± 6.13	19.25 ± 3.24	20.00 ± 3.73	19.24 ± 4.24
t	−3.832	−6.064	−6.722	−5.595	−6.883
p	0.000*	0.000*	0.000*	0.000*	0.000*

Note: Values are presented as mean ± standard deviation. Group 3 represents implants placed without the nut system, while Group 4 represents implants placed with the nut system. Comparisons were performed using independent samples *t*-tests (equal variances assumed). Negative *t* values indicate higher means in the nut-assisted group.
*$p < 0.05$ was considered statistically significant.

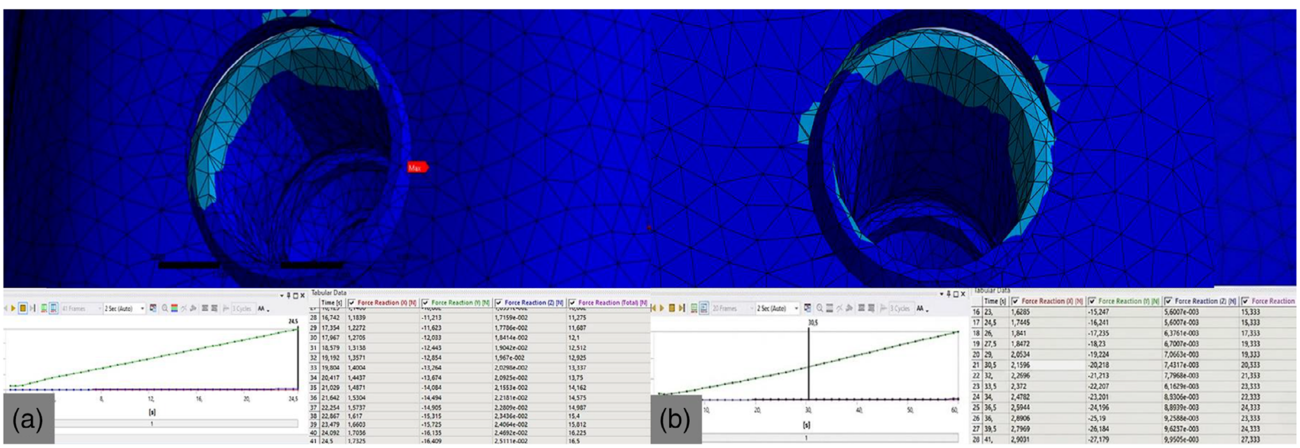

FIGURE 5 Finite element analysis showing the detachment points under vertical loading: (a) nut-free implant (M1)—16.5 N at 24.5 s; (b) nut-assisted implant (M2)—20.33 N at 30.5 s.

implant detached at 30.5 s under 20.33 N (Figure 5a,b). In M3, the implants detached at 20 s under a load of 15 N, whereas in M4, detachment occurred at 33.5 s under a load of 22.3 N. Accordingly, the reference load was set to 16.5 N for Models 1 and 2 and 15 N for Models 3 and 4, and these values were used in subsequent stress analyses. Based on these reference values, the maximum compressive stress (minimum principal stress) in M1 was measured as 117.53 MPa, whereas under the same loading conditions, M2 exhibited a slightly lower value of 112.10 MPa, indicating a more balanced transfer of stress to the surrounding bone tissue (Figure 6a,b). In M3, the maximum compressive stress was 141.64 MPa, while in M4, this value decreased to 107.47 MPa, demonstrating a significant reduction in stress concentration (Figure 6c,d). These findings suggest that the nut system effectively reduced maximum compressive stress in the bone, promoting a more homogeneous and physiologically favorable distribution of the applied load.

When the maximum von Mises stress values generated on the implants were compared, M1 exhibited a maximum stress of 97.301 MPa, while M2 showed a slightly lower value of 96.131 MPa (Figure 7a,b). In the dual-implant configuration, M3 showed a maximum implant stress of 120.34 MPa, whereas M4 demonstrated a substantially lower value of 86.737 MPa, indicating a significant reduction in stress concentration (Figure 7c,d).

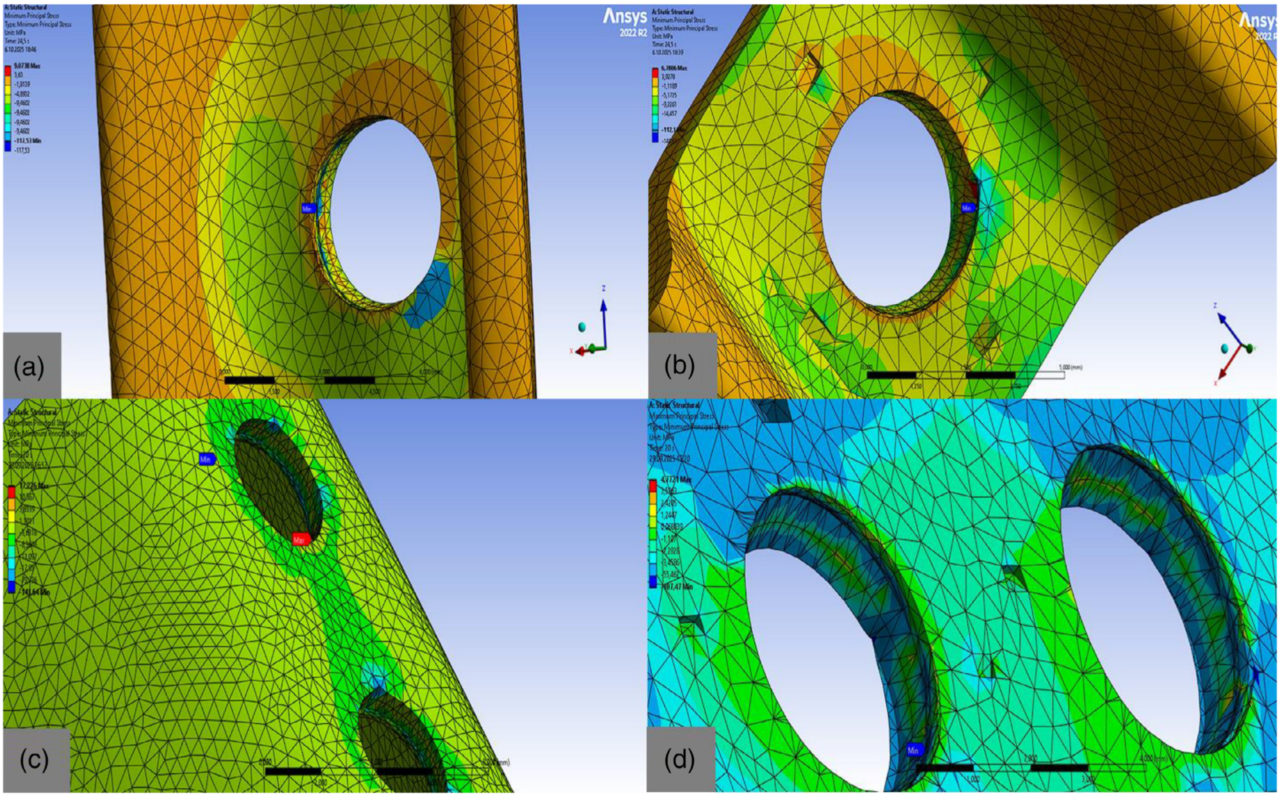

FIGURE 6 Finite element analysis showing the maximum compressive stress (minimum principal stress) distribution under vertical loading: (a) Under a 16.5 N load, the maximum compressive stress in the bone at the detachment point of the nut-free implant in region #16 was 117.53 MPa (M1). (b) Under the same 16.5 N load, the maximum compressive stress in the bone in region #16 was 112.10 MPa (M2). (c) Under a 15 N load, the maximum compressive stress in the bone at the detachment point of the nut-free implants in regions #26 and #27 was 141.64 MPa (M3). (d) Under a 15 N load, the maximum compressive stress in the bone around the nut-assisted implants placed in regions #26 and #27 was 107.47 MPa (M4).

DISCUSSION

Two-stage protocols may increase patient morbidity and overall treatment costs due to prolonged treatment duration and the need for multiple surgical interventions. Accordingly, when sufficient primary stability can be achieved, simultaneous sinus augmentation with implant placement is considered a more efficient and clinically advantageous approach.[15] In addition, short implants have been proposed as an alternative treatment option for the atrophic posterior maxilla.[20, 21] However, in cases with extremely limited residual bone height, the ability of short implants to achieve sufficient primary stability may be limited, thereby supporting the rationale for exploring alternative stabilization strategies.

In this context, the study focuses on severely atrophic posterior maxilla conditions in which achieving adequate primary stability with conventional implant placement may not be feasible. Therefore, the proposed system is not intended as an alternative to short implants, but rather as a potential stabilization strategy beyond their indication limits. Accordingly, a direct comparison was not performed.

From a clinical standpoint, the selection and success of implant treatment modalities in the atrophic posterior maxilla are fundamentally dependent on the ability to achieve adequate primary stability at the time of implant placement. When sufficient primary stability can be predictably obtained, conventional approaches—such as implant placement with or without sinus augmentation—remain reliable and widely accepted treatment options.

In contrast, when primary stability cannot be reliably achieved due to insufficient bone volume or quality, alternative treatment modalities—including transnasal, zygomatic, or pterygoid implants—may be considered. These approaches are generally reserved for advanced clinical scenarios, such as severe partial or total maxillary atrophy, failure of previous grafting or implant therapies, or situations in which conventional augmentation procedures are not feasible or not preferred by the patient (e.g., avoidance of grafting procedures).[22] Despite their potential advantages, including the possibility of graftless rehabilitation and reduced treatment time, these techniques are inherently complex and technique-sensitive. The success of such approaches is highly dependent on surgical expertise, and they are associated with a higher risk of intraoperative and postoperative complications. Therefore, their use should be limited to carefully selected cases and performed by clinicians with advanced anatomical knowledge and extensive surgical experience to ensure safe and predictable outcomes.[22–24]

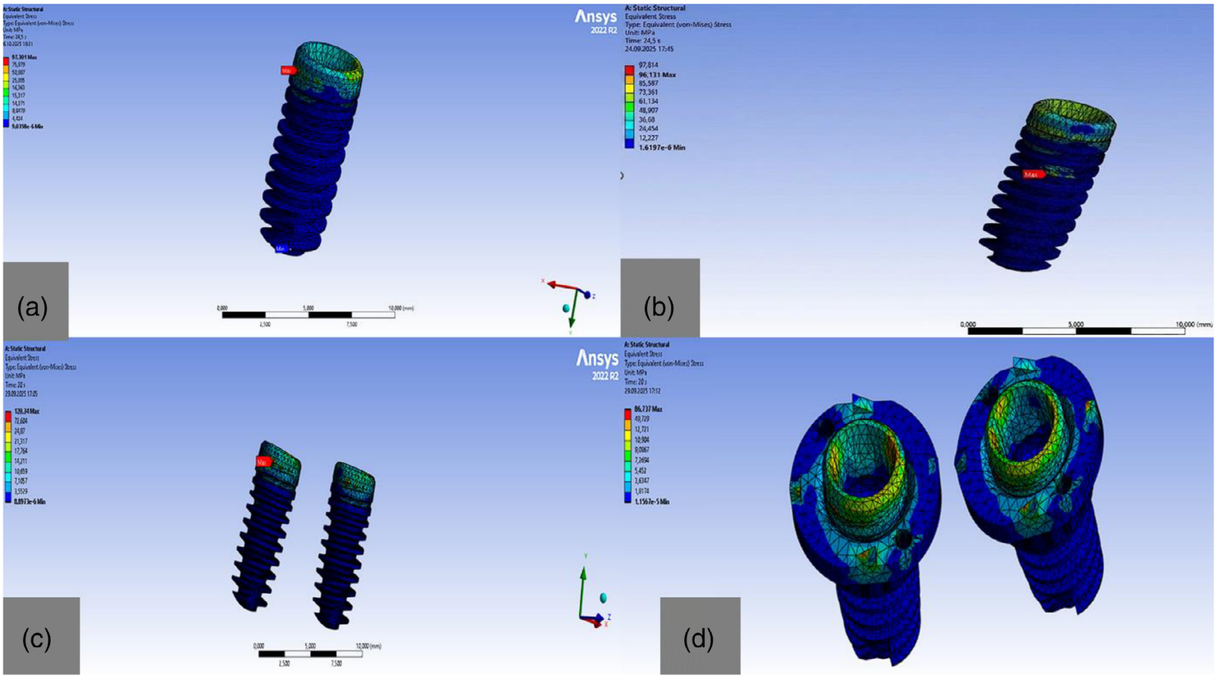

FIGURE 7 Finite element analysis showing the maximum von Mises stress distribution on the implants under vertical loading: (a) At the detachment point of the nut-free implant in region #16, the maximum von Mises stress observed on the implant was 97.301 MPa. (b) Under a 16.5 N vertical load, the maximum von Mises stress observed on the nut-assisted implant in region #16 was 96.131 MPa. (c) At the detachment point of the nut-free implants in regions #26 and #27, the maximum von Mises stress observed on the implants was 120.34 MPa. (d) Under a 15 N vertical load, the maximum von Mises stress observed on the nut-assisted implants in regions #26 and #27 was 86.737 MPa.

The implant nut system was developed as a biomechanical concept to address situations in which implant placement and stabilization are challenging with conventional approaches. Importantly, bone height alone is not a reliable predictor of implant stability. Therefore, rather than being defined by a fixed residual bone height threshold, the system is intended for cases in which adequate primary stability cannot be achieved with conventional implant placement, particularly in the posterior maxilla, where stability-compromised conditions are commonly associated with severely reduced residual bone height (e.g., <3 mm). The system was evaluated under controlled conditions using a preclinical model and 3D FEA to characterize its biomechanical behavior. Therefore, the findings should be interpreted not as direct evidence of clinical applicability, but as preliminary biomechanical data. A stability-driven clinical decision-making workflow summarizing these considerations is presented in Figure 8.

The experimental setup used in this study was designed to simulate the fundamental mechanical conditions of lateral sinus augmentation. In this model, the nut component was introduced into a sinus-like cavity via a lateral access pathway and positioned against a surface representing the sinus floor, allowing its behavior to be evaluated as an intra-sinus anchorage element. In addition, the knurled surface on the upper portion of the nut was designed to facilitate controlled manipulation with surgical instruments during placement and positioning. During implant insertion, stable and precise mechanical interlocking was achieved through thread compatibility and the chamfered seating interface between the implant and the nut, thereby enhancing retention against the simulated sinus floor.

Within this framework, several stabilization approaches have been described in the literature to address insufficient primary stability in the severely atrophic posterior maxilla. Grandi et al.[25] introduced the Sinus Implant Stabilization (SIS) plate to shorten treatment time and enhance primary stability by simultaneously performing sinus lifting and implant placement. Their findings suggested that implants with insufficient primary stability in the posterior maxilla could be rigidly stabilized at the crestal level. However, the applicability of this technique appears to be limited in cases involving second molar placement and horizontal ridge augmentation.

The implant stabilizer described by Dabija et al.[26] requires at least 3–4 mm of cortical support due to its limited structural rigidity. In addition, the supra-crestal positioning of the system has been associated with increased flap tension and a higher risk of wound dehiscence. Similarly, the “butterfly” titanium mesh system described by Filipov et al.[15] has been reported to pose surgical adaptation difficulties and potential soft-tissue complications.

The resorbable nut system described by Uçkan et al.[16] aimed to enhance stability in cases with low bone height; however, its clinical effectiveness remains uncertain due to the limited number of cases and the lack of long-term follow-up data. Likewise, the cortical satellite system described by Engelke et al.[17] failed to provide sufficient stability in

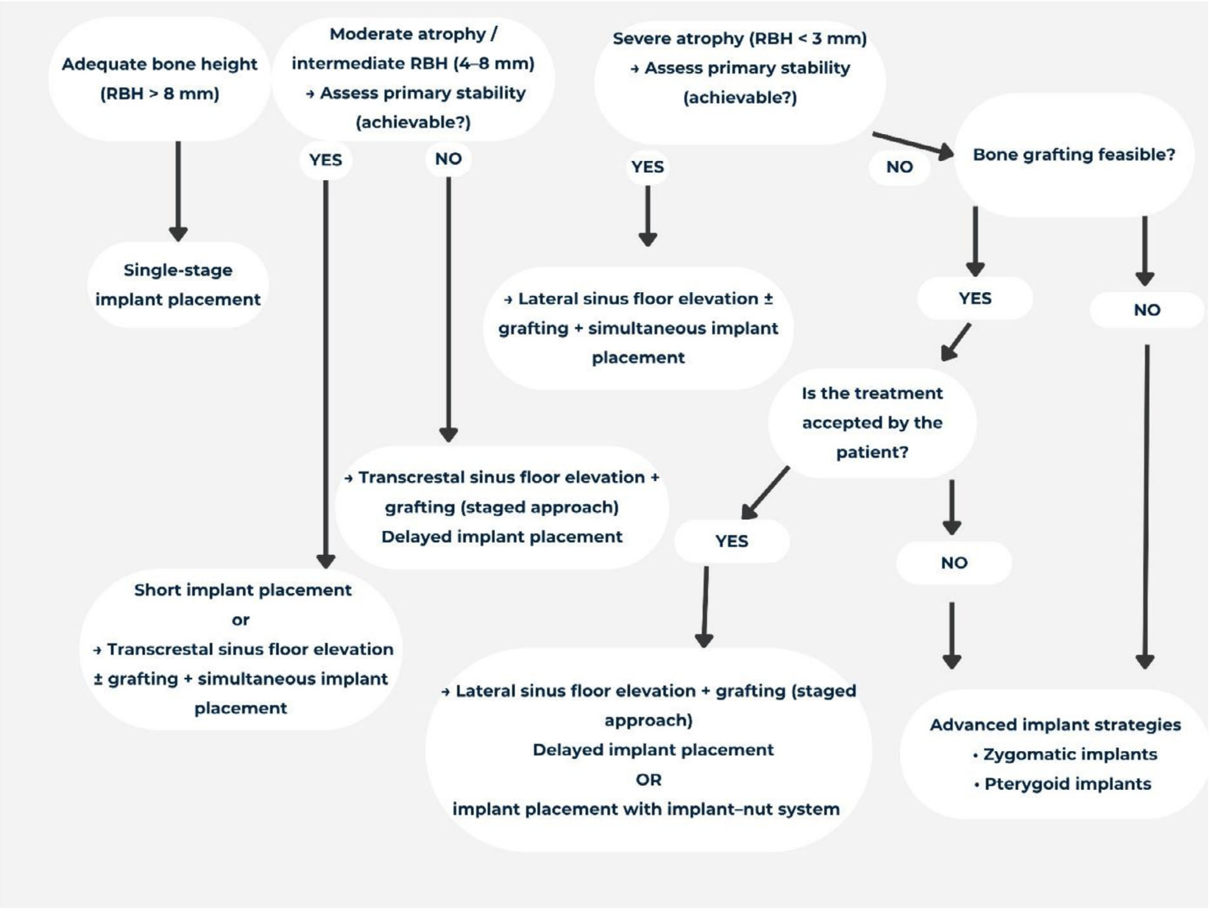

FIGURE 8 Conceptual clinical workflow for implant placement in the atrophic posterior maxilla. Note: The implant nut system is presented as an experimental, preclinical stabilization concept and is included for conceptual illustration only. It does not represent a clinically validated treatment option.

regions with cortical bone thickness below 2 mm, as deformation of the microplate under load limited its effectiveness to temporary stabilization.

In addition, graft-based approaches such as the Fit Lock technique reported by Vittorini-Velasquez et al.[27] and bicortical stabilization using autogenous bone blocks described by Salehi et al.[28] have demonstrated improved primary stability; however, these methods are associated with increased surgical invasiveness, prolonged operative time, donor site morbidity, and potential complications such as graft fracture.

In contrast to these approaches, the implant nut system evaluated in the present study represents a mechanical stabilization concept based on anchorage to the cortical bone of the sinus floor. The system is designed to provide retention-based stabilization through thread compatibility between the implant and the nut, as well as claw-like extensions intended to establish contact with the sinus floor.

The feasibility of this concept is supported by findings from experimental evaluations conducted on polyurethane models simulating a severely atrophic posterior maxilla with approximately 1 mm of cortical bone. Within this experimental model, the system was associated with a 67.5% increase in primary stability in the single-nut configuration and a 72.8% increase in the double-nut configuration.

From a mechanical perspective, the positioning of the nut component within the cortical bone may enhance stability under simulated conditions. However, the extent to which this may reduce the need for additional fixation in clinical settings remains uncertain and requires further investigation. The potential clinical applicability of the system remains hypothetical and may be influenced by several surgical variables, including controlled manipulation within the sinus cavity, accurate positioning, and the ability to reposition the component safely when necessary. In addition, factors such as membrane integrity, surgical accessibility, sinus anatomy, and operator experience may further affect its clinical performance.

Although the technique is compatible with conventional sinus lift workflows, it involves intra-sinus placement of an additional component, requiring precise handling and positioning. In particular, maintaining control of the component and ensuring proper interaction with the implant may require technical sensitivity. However, the design features, including a safety hole for suture-assisted control and a knurled surface facilitating instrument handling, may support intraoperative manipulation. Therefore, careful surgical technique and operator experience are likely to be important factors in the potential clinical use of this approach.

Potential intraoperative risks, such as unintended displacement of the component into the sinus cavity or challenges related to positioning and retrieval, should be acknowledged. However, the system's design characteristics, including features that facilitate controlled manipulation, may help mitigate these risks. In the present study, the knurled surface enabled controlled handling with surgical instruments during polyurethane-based experimental testing. Nevertheless, although these findings were favorable under experimental conditions, they should not be directly generalized to clinical scenarios without further in vivo and clinical validation.

Despite the absence of in vivo validation, the present findings contribute to understanding the mechanical behavior of the system. The observed increase in primary stability and more favorable stress distribution may be considered biomechanically relevant parameters associated with implant stability. In this respect, the current results provide preclinical data that may serve as a basis for future in vivo and prospective clinical studies.

To support the mechanical validity of this preclinical framework, polyurethane study models are widely used as synthetic bone substitutes in biomechanical testing, particularly for the analysis of dental implant stability. According to the ASTM F1839-08 (1997) standard issued by the American Society for Testing and Materials (ASTM), these models exhibit mechanical and physical properties similar to natural bone tissue due to their homogeneous structure and high mechanical stability, allowing for noninvasive, reliable, and reproducible evaluation of implant stability and bone–implant interactions.[12, 18]

In the model study conducted by Comuzzi et al.[2], implants placed in 1-mm-thick polyurethane blocks with densities of 20 and 30 pcf exhibited mean ISQ values of 19.2–20.4. In the present study, the mean ISQ values were 10.91 and 11.13 in Groups 1 and 3, and 18.27 and 19.24 in Groups 2 and 4, respectively. These findings indicate that the nut system significantly enhanced primary stability. However, the lower RFA values observed compared with those reported by Comuzzi et al. may be attributed to differences in the drilling protocol. While Comuzzi et al. used a 3.2 mm final drill for 4.4 mm-diameter implants, a 3.7 mm final drill for 4.1 mm implants was employed in the present study to evaluate the effect of the nut system better. This may have increased the osteotomy gap, thereby resulting in relatively lower ISQ measurements.

3D-FEA is commonly used in dental research, providing a useful tool for simulating complex anatomical structures and evaluating their mechanical behavior.[29, 30] In FEA, stress distribution is highly dependent on the mechanical properties assigned to the modeled materials. However, due to the absence of universally accepted standards for the elastic modulus and Poisson's ratio of cortical and trabecular bone, these tissues are commonly simplified as homogeneous, isotropic, and linearly elastic to facilitate numerical analysis. All models in the present study were constructed based on these assumptions.[31–35] These assumptions were adopted in accordance with commonly used approaches in previous studies to facilitate computational modeling. However, they should be considered a limitation, as they do not fully reflect the complex, heterogeneous, and anisotropic nature of human bone.

Anatomically accurate models were used to enhance the reliability of the finite element simulations.[36] Although a mesh density of 30,000–200,000 elements is generally considered adequate, 266,285 elements and 158,894 nodes were used in the present study to improve solution accuracy. Nonlinear analysis was performed to account for contact separation and frictional interactions between the implant, nut, and bone, with a friction coefficient of 0.3.[37–39] Incremental loading was applied to determine the critical detachment force and to evaluate the contribution of the nut system to primary stability.

In the interpretation of the FEA results, equivalent stress (von Mises stress) was used as the primary evaluation criterion for ductile materials, such as metallic implants, whereas principal stresses were considered for brittle materials, such as bone.[33, 40] Pmax represents the maximum tensile stress, while Pmin denotes the maximum compressive stress. When the absolute values of the principal stresses are compared, the dominant stress state is determined by the higher-magnitude principal stress.[33] In the present study, compressive stresses in the bone exhibited higher absolute values; therefore, the analyses were primarily interpreted based on compressive stress distribution.

Yang et al.[41] evaluated winged short implants in a severely atrophic maxilla with 1 mm of bone height using FEA and reported that the planar design was associated with lower stress values. However, the requirement for customized fabrication of these implants may limit their cost-effectiveness and clinical applicability. In a comparable simulation context, the present study demonstrated that the use of the nut system was associated with increased stability and more homogeneous stress distribution under the simulated conditions. In addition, the system's compatibility with standard implant diameters may enable more accessible manufacturing processes, potentially translating into a cost advantage over custom-designed systems.

In a study by Yan et al. using FEA, it was reported that when the residual alveolar bone height decreased below 4 mm, stress and displacement values nearly doubled, potentially increasing the risk of implant failure.[42] In the present study, a more severely atrophic condition was investigated by simulating a scenario with a residual bone height of approximately 1 mm.

In the present study, the maximum compressive stress around the implant neck was 117.53 MPa in Model 1, 112.1 MPa in Model 2, 141.64 MPa in Model 3, and 107.47 MPa in Model 4. These findings suggest that the application of the nut system was associated with an approximately 5% reduction in stress in single-implant models and a 24% reduction in double-implant models. The more pronounced reduction observed in double-implant configurations may be related to the broader contact surface formed between the two nuts and the bone, potentially allowing improved adaptation to the sinus floor morphology. This increased contact area may also have contributed to a higher force required for implant detachment, with increases of 48% in double-implant models and 23% in single-implant models.

Accordingly, while the nut system was associated with increased stability in both configurations, this effect appeared more pronounced in the double-nut design, where bone–nut contact was greater and more evenly distributed. These findings are consistent with results from polyurethane model experiments and, when considered together, indicate a consistent trend in the stabilizing effect of the nut system under the experimental and simulated conditions. From a biomechanical perspective, the proposed system may be associated with improved mechanical stability and a more homogeneous stress distribution at the implant–bone interface under simulated conditions. However, these assessments are based solely on numerical modeling and experimental conditions; therefore, their interpretation in a clinical context remains limited in the absence of biological validation.

It is well established that excessive micromotion and high interfacial strain may impair osseointegration and lead to fibrous tissue formation when critical thresholds are exceeded.[43, 44] In this context, the improved mechanical stability and more homogeneous stress distribution observed in the present study may help limit micromotion at the interface under simulated conditions. The claw-like extensions were designed to provide mechanical anchorage within cortical bone while distributing forces over a broader contact area. However, the biological response of bone to these mechanical interactions, including osseointegration and remodeling, was not evaluated in this study.

The FEA conducted in the present study has several inherent limitations that should be acknowledged. While real bone tissue exhibits heterogeneous, anisotropic, and viscoelastic properties, the models used in this study, consistent with commonly adopted approaches in the literature, were constructed under homogeneous, isotropic, and linear-elastic assumptions to facilitate computational modeling and ensure reproducibility.[31] Material properties, including the elastic modulus and Poisson's ratio, were derived from commonly reported values to ensure standardization; however, this approach does not account for individual variability or pathological conditions. In addition, although polyurethane materials provide advantages in terms of standardization and reproducibility, they do not fully replicate the biomechanical complexity of human bone or technique-dependent factors.[18, 45] Furthermore, no biological validation was performed; therefore, essential processes such as osseointegration, bone remodeling, and healing response were not evaluated.

Accordingly, the findings should be interpreted as preliminary biomechanical data obtained under controlled experimental and computational conditions rather than direct evidence of clinical performance, and they cannot be directly translated into clinical outcomes.

CONCLUSIONS

In the present study, implants supported by the nut system demonstrated higher ISQ values across all measurement directions, indicating improved primary stability. This effect was observed in both single- and double-implant configurations, with a more pronounced trend in double-implant models, which may be related to the increased bone–nut contact area. FEA further revealed a trend toward more favorable stress distribution and reduced compressive stress concentration in the surrounding bone under simulated conditions.

Within the limitations of this preclinical study, these findings should not be interpreted as evidence of clinical performance, but rather as preliminary biomechanical data derived under controlled experimental and computational conditions. The proposed implant nut system may represent a potential mechanical stabilization concept for challenging clinical scenarios; however, its biological response and clinical applicability remain to be established through well-designed in vivo (including animal) and prospective clinical studies.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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