Optimizing Edentulous Mandible Rehabilitation: A Biomechanical Evaluation of Three Implant-Supported Fixed Restoration Techniques

Abstract

Objective
This study aimed to evaluate the biomechanical performance of different implant configurations for three-implant-supported rehabilitation of the edentulous mandible using three-dimensional finite element analysis. Specifically, conventional vertical bone-level and tissue-level implants were compared with the Trefoil system and the All-on-3 configuration that incorporates posteriorly tilted implants.

Materials and Methods
A patient-specific mandibular model was reconstructed from cone-beam computed tomography data. Four implant-supported full-arch scenarios were simulated: three bone-level implants (3BL), three tissue-level implants (3TL), the Trefoil system (TRF), and the All-on-3 configuration (ALL3). Prostheses were standardized with identical emergence profiles and bilateral cantilever extensions. A vertical occlusal load of 100 N was applied through a spherical body mimicking a food bolus. Stress distribution in cortical bone, trabecular bone, and implant structures was assessed using finite element analysis software.

Results
The All-on-3 configuration produced the highest compressive and tensile stresses in both peri-implant bone and implant components. Bone-level designs generally resulted in greater stress accumulation, particularly in cortical bone. In contrast, tissue-level implants demonstrated more favorable stress distribution. Among all models, the Trefoil system consistently exhibited the lowest stress concentrations, reflecting its geometric and prosthetic design advantages.

Conclusion
Vertically positioned tissue-level implants and the Trefoil system demonstrated superior biomechanical performance in three-implant-supported mandibular rehabilitations with cantilever extensions. Conversely, the All-on-3 design with posteriorly tilted implants was associated with increased stress levels that may negatively impact long-term prosthetic stability. Careful selection of implant type, diameter, and angulation is therefore essential for optimizing treatment outcomes in reduced-implant full-arch rehabilitation.

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Keywords

Finite Element Analysis, Edentulous Mandible, Implant-Supported Prostheses, Biomechanics, Dental Implants, Stress Distribution.

INTRODUCTION

Rehabilitation of the completely edentulous mandible remains one of the most challenging aspects of implant dentistry. Successful outcomes require treatment strategies that balance surgical invasiveness, cost, and long-term predictability while restoring adequate function and esthetics. In recent decades, there has been a growing trend toward reducing the number of implants in full-arch prosthetic rehabilitations, with the goal of minimizing morbidity, lowering financial burden, and increasing accessibility for aging or medically compromised populations (1).

Posterior mandibular resorption is a frequent obstacle to implant placement in edentulous patients. While augmentation procedures such as guided bone regeneration or nerve lateralization may overcome anatomical limitations, these interventions are associated with higher complication rates, prolonged treatment time, and increased costs (2). Consequently, the anterior mandible, and specifically the interforaminal region, has become the preferred site for implant placement due to its relatively preserved bone volume, dense cortical structure, and favorable healing potential (3).

Historically, the Brånemark Novum concept, introduced in the 1990s, represented a milestone by enabling immediate loading of three implants with a prefabricated framework (5,6). Building on this foundation, the Nobel Biocare Trefoil™ system was later developed, incorporating wide-diameter tissue-level implants and a prefabricated bar to simplify surgical procedures and reduce treatment duration (4-6). In parallel, angled implant placement strategies were introduced to maximize the use of available bone and bypass anatomical limitations, leading to the emergence of the All-on-3 configuration, which adapts principles from the widely adopted All-on-4 protocol by combining one axial and two tilted implants (7-9).

Despite the clinical adoption of these reduced-implant approaches, concerns remain regarding their biomechanical reliability. Cantilever extensions and tilted implant configurations may generate unfavorable stress distributions, resulting in increased stress on peri-implant bone, implants and prosthetic components. Excessive or uneven stress distribution has been associated with mechanical complications, marginal bone loss, and reduced long-term stability (10-14). Understanding the mechanical behavior of these designs is therefore critical for optimizing long-term outcomes.

Three-dimensional finite element analysis provides a non-invasive and reproducible method to model stress distribution under controlled functional loading, offering valuable insights into the biomechanical implications of different implant configurations (11, 15, 16).

The aim of this study was to evaluate and compare the biomechanical performance of four three-implant-supported full-arch configurations for the edentulous mandible using three-dimensional finite element analysis. The configurations included three vertically placed bone-level implants, three vertically placed tissue-level implants, the Trefoil system with system-specific wide-diameter implants, and the All-on-3 configuration with angled posterior implants. The null hypothesis tested was that no significant biomechanical differences would be observed among these four treatment models.

MATERIALS AND METHODS

Model Construction and Virtual Simulation

This study employed three-dimensional finite element analysis (3D FEA) to evaluate the biomechanical behavior of different implant-supported fixed prosthetic designs for the rehabilitation of a completely edentulous mandible. The virtual mandibular model was generated from anonymized cone beam computed tomography (CBCT) data of an adult patient presenting with posterior vertical bone atrophy and sufficient bone volume in the interforaminal region. Because only de-identified imaging data and computer-based simulations were used, ethical approval and informed consent were not required.

High-resolution CBCT images were acquired at 1.0 mm slice thickness and exported in Digital Imaging and Communications in Medicine (DICOM) format. The data were processed in VRMesh (VirtualGrid, Bellevue, WA, USA) and Rhinoceros 3D (McNeel North America, Seattle, WA, USA) software to create an anatomically realistic model of the mandible. The model included trabecular bone enclosed within a cortical shell. Standardized dimensions were applied: alveolar crest width of 8 mm; vertical bone height of 6 mm from the crest to the mandibular canal in the posterior region and 14 mm in the interforaminal region. The mental foramina were positioned 25 mm bilaterally from the midline (interforaminal distance: 50 mm). Vertical distances from the mental foramen to the superior and inferior mandibular borders measured 7 mm and 4 mm, respectively. Each foramen was modeled as a 3 mm opening. To replicate soft tissue, a uniform mucosal layer of 2 mm was applied over the alveolar crest.

Implant and Prosthesis Modeling

Three commercially available implant systems were selected to represent different clinical approaches:

- **Nobel Biocare Active** (Nobel Biocare, Kloten, Switzerland) (4.3 × 11.5 mm; bone-level)
- **Straumann Tissue Level** (Straumann Holding AG, Basel, Switzerland) (4.1 × 12 mm; tissue-level, 2.8 mm polished collar)
- **Nobel Biocare Trefoil** (Nobel Biocare, Kloten, Switzerland) (5.0 × 11.5 mm; tissue-level, 4.5 mm polished collar)

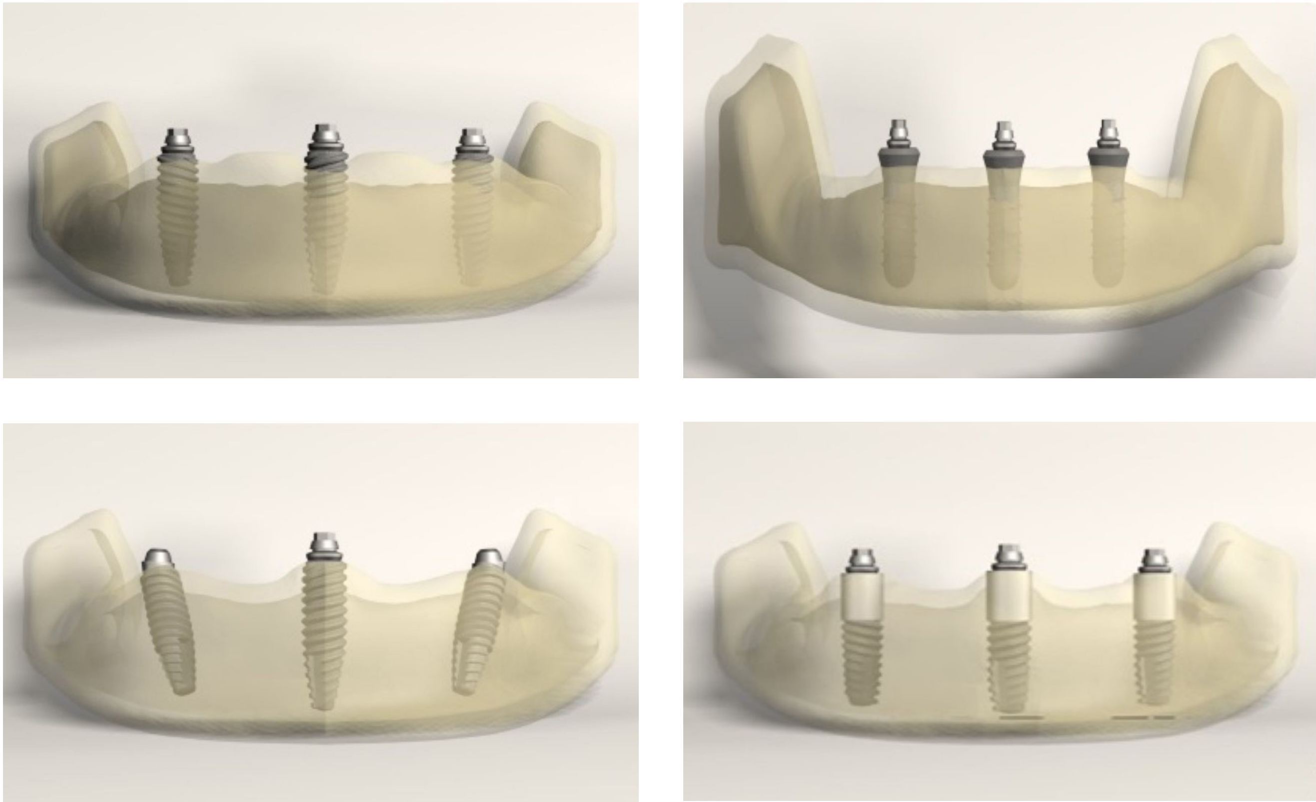


Fig. 1 Three-dimensional finite element models created for the study: **A**) three bone-level implants (3BL), **B**) three tissue-level implants (3TL), **C**) All-on-3 configuration with posteriorly tilted implants (ALL3), and **D**) Trefoil system with system-specific implants (TRF).

Implants and prosthetic components were digitized with the Dental Wings DW-7-140 optical 3D scanner (Dental Wings Inc., Montreal, Canada; accuracy 10 μm) and imported into VRMesh. Four configurations were modeled (Figure 1):

1. **3BL** – Three vertically placed bone-level implants (Nobel Active).
2. **3TL** – Three vertically placed tissue-level implants (Straumann Tissue Level).
3. **TRF** – Trefoil system with system-specific tissue-level implants and prefabricated framework.
4. **ALL3** – One vertical implant with two posteriorly tilted bone-level implants (All-on-3 concept).

For all models, standardized prosthetic emergence points were established, and full-arch prostheses with bilateral cantilever extensions of identical length were designed. Models were finalized in Rhinoceros 4.0 (McNeel North America, Seattle, WA, USA) using Boolean operations to ensure accurate integration of bone, implants, abutments, and prosthetic frameworks.

Material Properties and Boundary Conditions

All modeled structures were assumed to be homogeneous, isotropic, and linearly elastic. Elastic moduli and Poisson's ratio values for cortical bone, trabecular bone, titanium alloy, and prosthetic materials were assigned according to validated values reported in the literature (15). A condition of perfect osseointegration (100% bone–implant contact) was assumed.

The mandibular base was fully constrained in all degrees of freedom to replicate anatomical fixation. Meshing was performed using 10-node second-order tetrahedral elements. Depending on the configuration, element counts ranged between 3.38 and 4.16 million, and nodes between 6.24 and 7.62 million, ensuring adequate resolution for stress evaluation.

Loading Conditions and Finite Element Analysis

Static analyses were carried out using ALGOR FEMPRO (ALGOR Inc., Pittsburgh, PA, USA). A vertical occlusal load of 100 N was applied through a spherical object 12 mm in diameter to mimic a food bolus. Two functional loading scenarios were simulated (Figure 2):

- **Anterior loading:** applied to the left mandibular canine to simulate cutting forces.
- **Posterior loading:** applied to the left mandibular first molar to simulate grinding forces.

Stress Evaluation Criteria

Stress distribution was assessed using three parameters:

- **Maximum principal stress (Pmax):** tensile stresses in bone.
- **Minimum principal stress (Pmin):** compressive stresses in bone.
- **von Mises stress (vM):** combined stresses in im-

plant and prosthetic components.

All stresses were expressed in megapascals (MPa). Fatigue thresholds for cortical bone were assumed as 115 MPa for tensile and 151 MPa for compressive stress (17).

Data Analysis and Interpretation

As finite element analysis is a deterministic computational approach without random variability, no statistical analyses were performed. Results were evaluated based on peak stress values and qualitative distribution patterns displayed as color-mapped visualizations. Comparative interpretation focused on identifying biomechanically critical regions, with reference to fatigue thresholds and risk of overload, to determine the implant configuration most favorable for stress management and long-term stability.

RESULTS

Finite element analysis revealed distinct stress distribution patterns across the four implant-supported mandibular configurations (3BL, 3TL, TRF, and ALL3) under anterior and posterior functional loading. Stress responses were evaluated in cortical

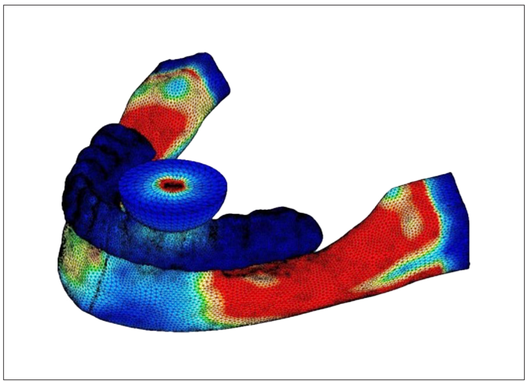
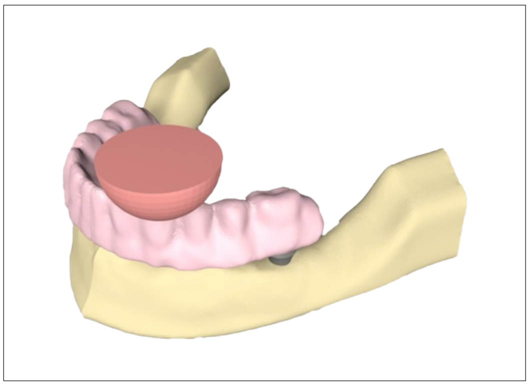
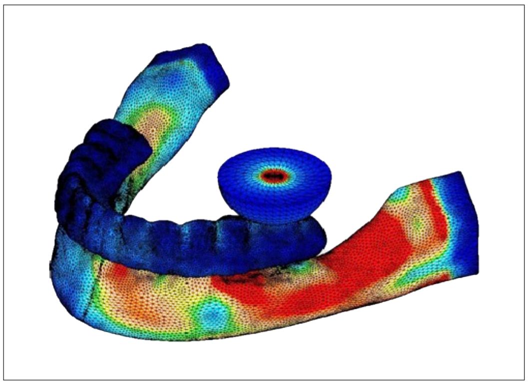
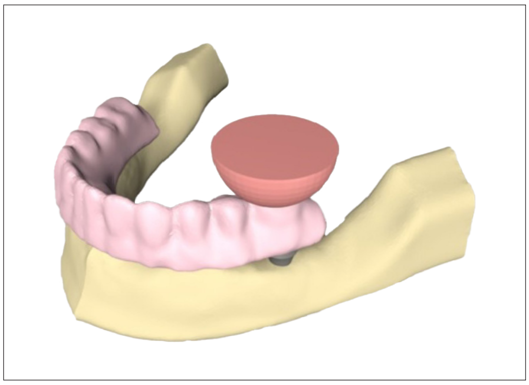
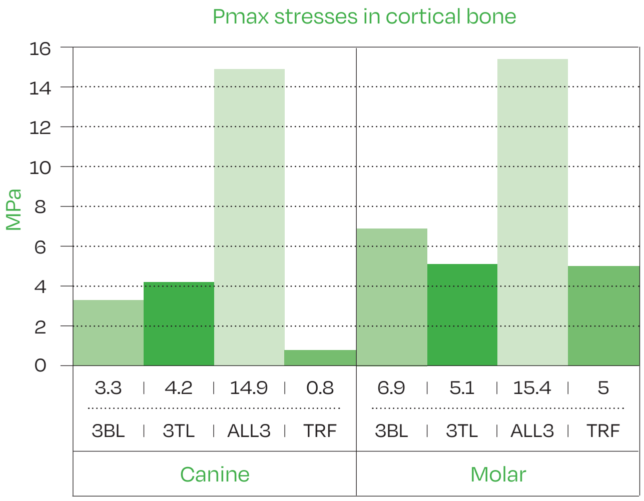





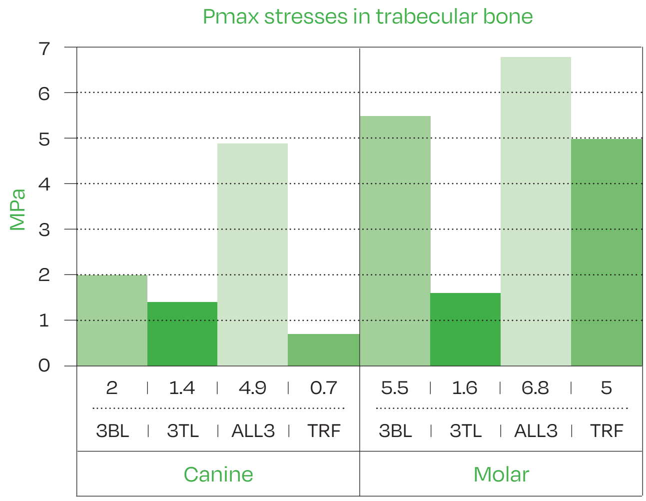
Fig. 2 Simulation of functional loading: a vertical occlusal force of 100 N was applied using a semi-spherical object to replicate the natural dynamic effect of a food bolus.

Tab. 1 Maximum compressive stresses in the cortical bone under anterior (canine) and posterior (molar) loading across all implant models.

Tab. 2 Maximum compressive stresses in the trabecular bone under anterior (canine) and posterior (molar) loading across all implant models.



Tab. 1



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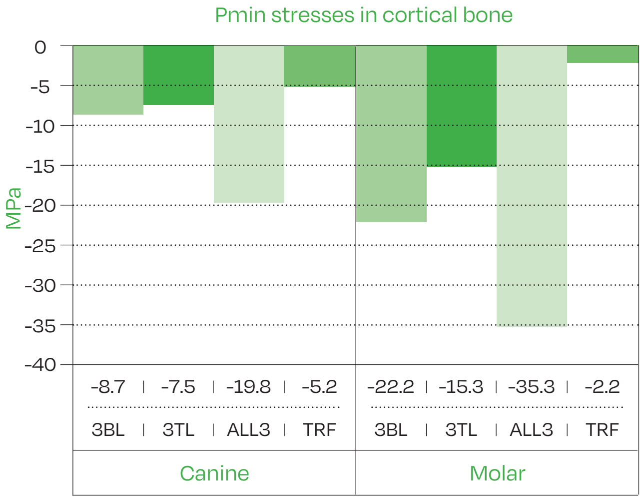

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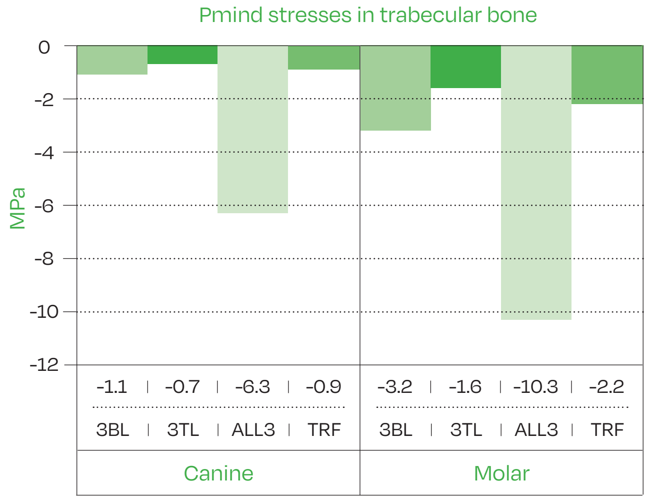

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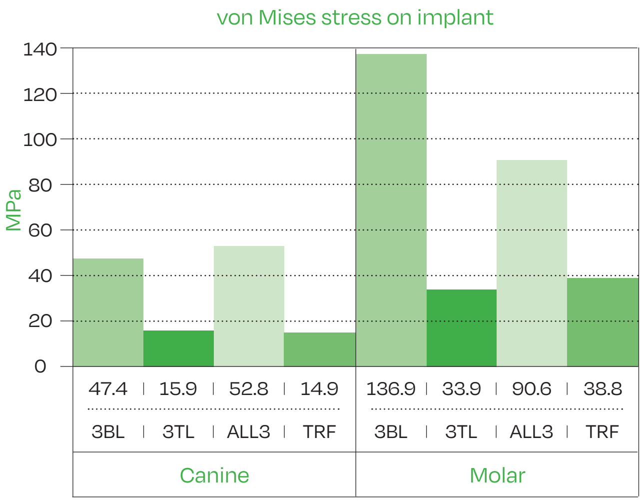

Tab. 5

bone, trabecular bone, and implant structures, with detailed outcomes summarized in Tables 1–5 and illustrated in Figures 1–12.

Compressive stresses in cortical bone

Under anterior loading, the ALL3 model exhibited the highest cortical compressive stress (14.9 MPa), whereas the 3BL (4.2 MPa) and 3TL (3.3 MPa) models showed lower values, and the TRF configuration demonstrated the most favorable outcome (0.8 MPa) (Figure 3, Table 1). When posterior loading was applied, compressive stresses again peaked in the ALL3 model (15.3 MPa), followed by 3BL (6.9 MPa), 3TL (5.1 MPa), and TRF (5.0 MPa) (Figure 5, Table 1).

Compressive stresses in trabecular bone

Similar patterns were observed in trabecular bone. With anterior loading, the ALL3 model reached 4.9 MPa, substantially higher than 3BL (2.0 MPa), 3TL (1.4 MPa), and TRF (0.7 MPa) (Figure 4, Table 2). Posterior loading amplified compressive stresses, with ALL3

Tab. 3
Maximum tensile stresses in the cortical bone under anterior (canine) and posterior (molar) loading across all implant models.

Tab. 4
Maximum tensile stresses in the trabecular bone under anterior (canine) and posterior (molar) loading across all implant models.

Tab. 5
von Mises stresses in implants under anterior (canine) and posterior (molar) loading across all implant models.

Fig. 3A-3D
Maximum compressive stresses in the cortical bone under anterior (canine) loading across all models.

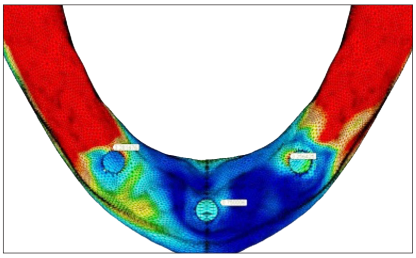

Fig. 3A

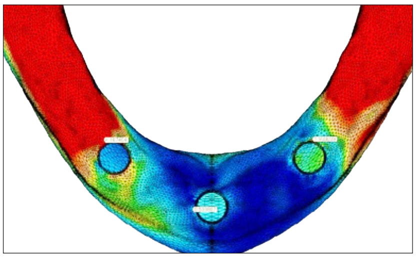

Fig. 3B

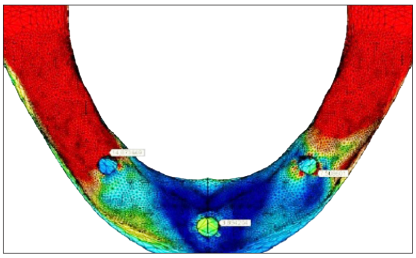

Fig. 3C

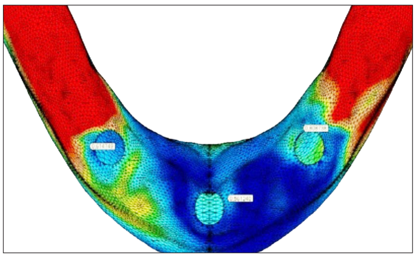

Fig. 3D

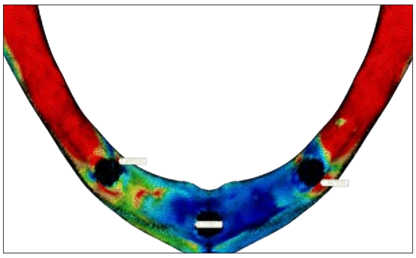

Fig. 4A

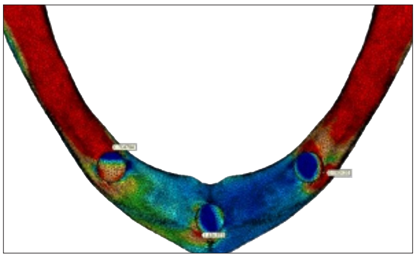

Fig. 4B

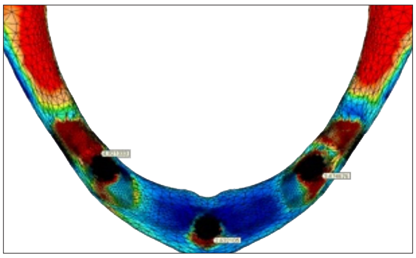

Fig. 4C

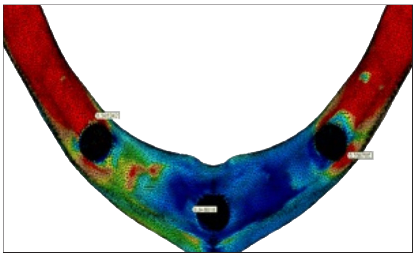

Fig. 4D

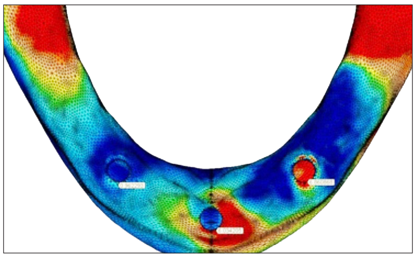

Fig. 5A

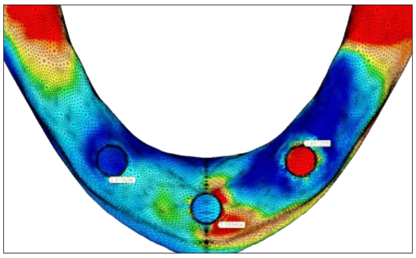

Fig. 5B

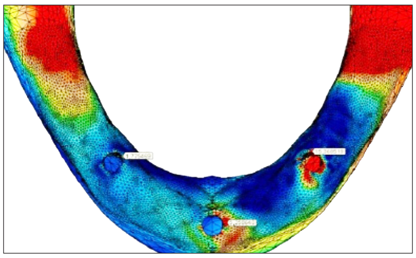

Fig. 5C

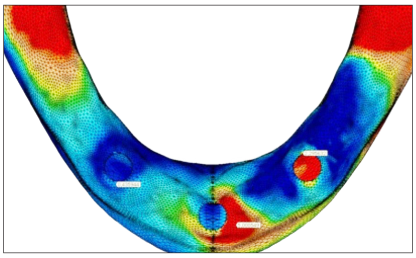

Fig. 5D

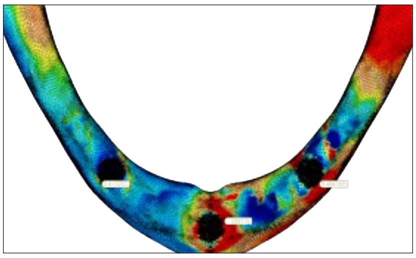

Fig. 6A

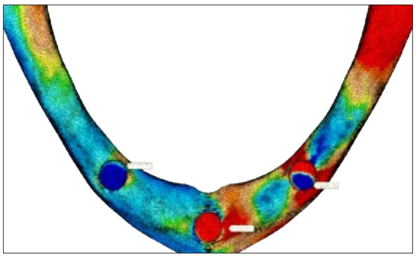

Fig. 6B

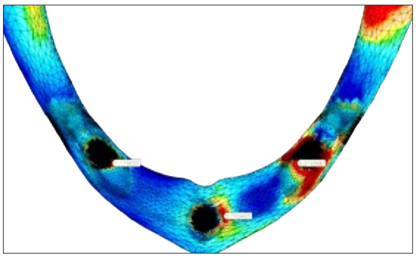

Fig. 6C

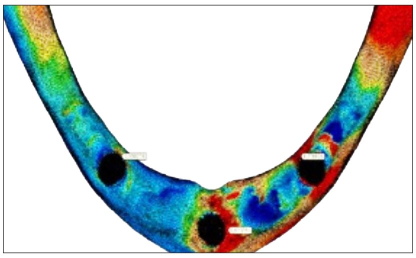

Fig. 6D

Fig. 4A-4D Maximum compressive stresses in the trabecular bone under anterior (canine) loading across all models.

Fig. 5A-5D Maximum compressive stresses in the cortical bone under posterior (molar) loading across all models.

Fig. 6A-6D Maximum compressive stresses in the trabecular bone under posterior (molar) loading across all models.

(6.8 MPa) and 3BL (5.5 MPa) recording the highest values, compared with markedly lower stresses in 3TL (1.7 MPa) and TRF (1.8 MPa) (Figure 6, Table 2).

Tensile stresses in cortical bone

In cortical bone, anterior loading generated the greatest tensile stress in the ALL3 model (−19.8 MPa), followed by 3BL (−8.7 MPa), 3TL (−7.5 MPa), and TRF (−5.2 MPa) (Figure 7, Table 3). Posterior loading further increased tensile stresses, with ALL3 producing a maximum of −35.7 MPa, in contrast to the relatively low levels recorded in 3BL (−3.2 MPa), TRF (−2.2 MPa), and 3TL (−1.6 MPa) (Figure 9, Table 3).

Tensile stresses in trabecular bone

In trabecular bone, anterior loading resulted in the highest tensile stress in the ALL3 model (−6.3 MPa). The 3BL (−1.1 MPa), TRF (−0.9 MPa), and 3TL (−0.7 MPa) models demonstrated considerably lower values (Figure 8, Table 4). Posterior loading reproduced this trend: ALL3 reached −10.3 MPa, followed by 3BL (−3.2 MPa), while TRF (−2.2 MPa) and 3TL (−1.6 MPa) maintained the lowest stresses (Figure 10, Table 4).

Von Mises stresses in implants

Implant stresses were strongly influenced by implant type and configuration. Under anterior loading, von

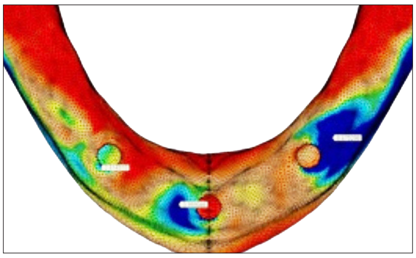

Fig. 7A

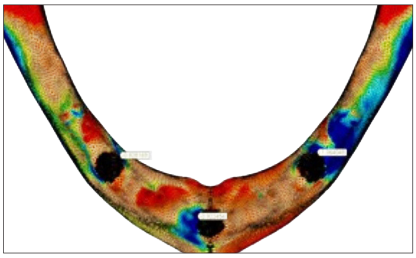

Fig. 8A

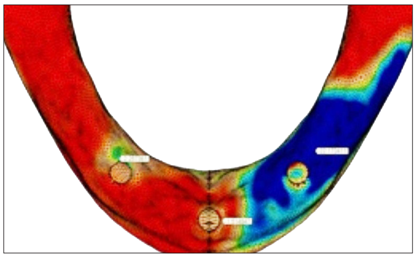

Fig. 9A

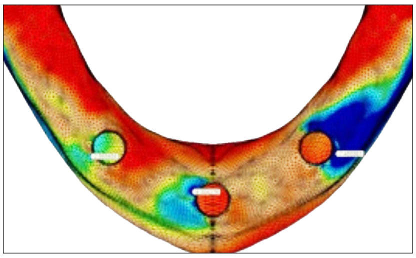

Fig. 7B

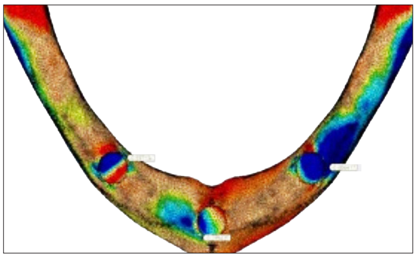

Fig. 8B

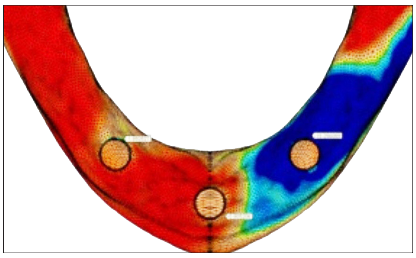

Fig. 9B

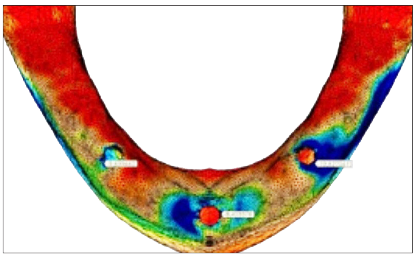

Fig. 7C

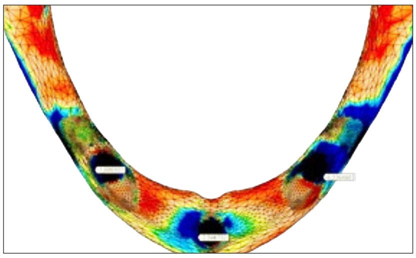

Fig. 8C

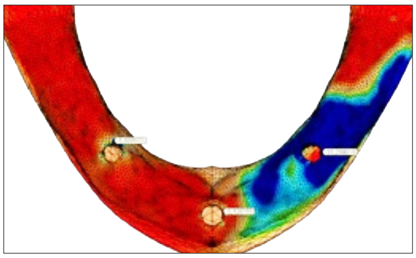

Fig. 9C

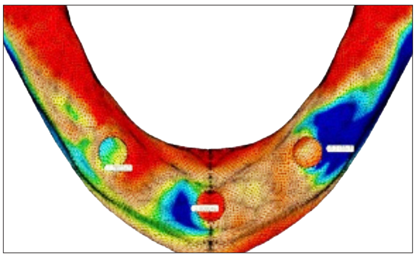

Fig. 7D

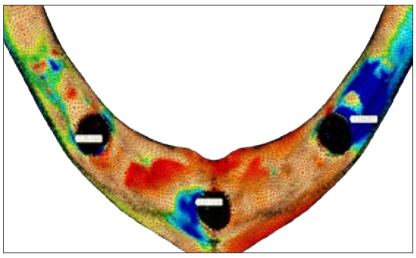

Fig. 8D

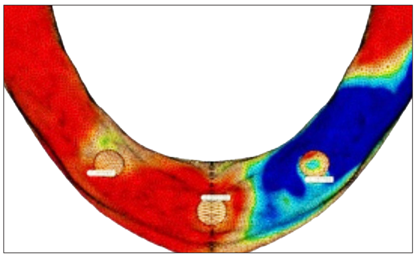

Fig. 9D

Fig. 7A-7D Maximum tensile stresses in the cortical bone under anterior (canine) loading across all models.

Fig. 8A-8D Maximum tensile stresses in the trabecular bone under anterior (canine) loading across all models.

Fig. 9A-9D Maximum tensile stresses in the cortical bone under posterior (molar) loading across all models.

Mises stresses were highest in the bone-level designs, with ALL3 (52.8 MPa) and 3BL (47.4 MPa), while tissue-level designs demonstrated much lower stresses: TRF (14.9 MPa) and 3TL (15.9 MPa) (Figure 11, Table 5). Regardless of configuration, the implant closest to the load application site bore the greatest stress concentration. Posterior loading substantially increased implant stresses in bone-level models, with 3BL reaching the highest value (136.9 MPa), followed by ALL3 (90.6 MPa). By contrast, TRF (38.8 MPa) and 3TL (33.9 MPa) maintained low stress levels (Figure 12, Table 5).

Summary of findings

Across all simulations, the ALL3 configuration consistently produced the highest compressive and tensile stresses in both cortical and trabecular bone, as well as the highest implant stresses, particularly under posterior loading. By contrast, the TRF system demonstrated the most favorable biomechanical performance, consistently generating the lowest stress values. The 3TL model also exhibited advantageous stress distribution compared with the 3BL model, underscoring the mechanical benefits of tissue-level implant designs.

DISCUSSION

This three-dimensional finite element analysis study

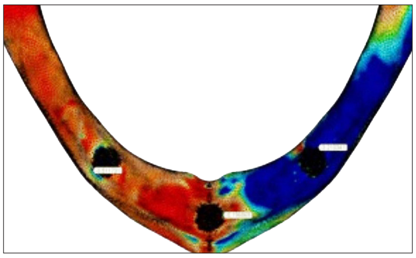

Fig. 10A

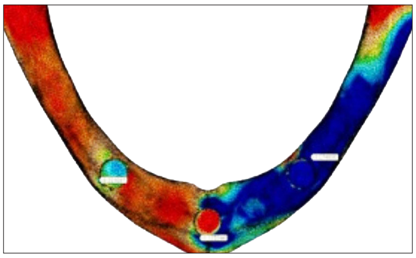

Fig. 10B

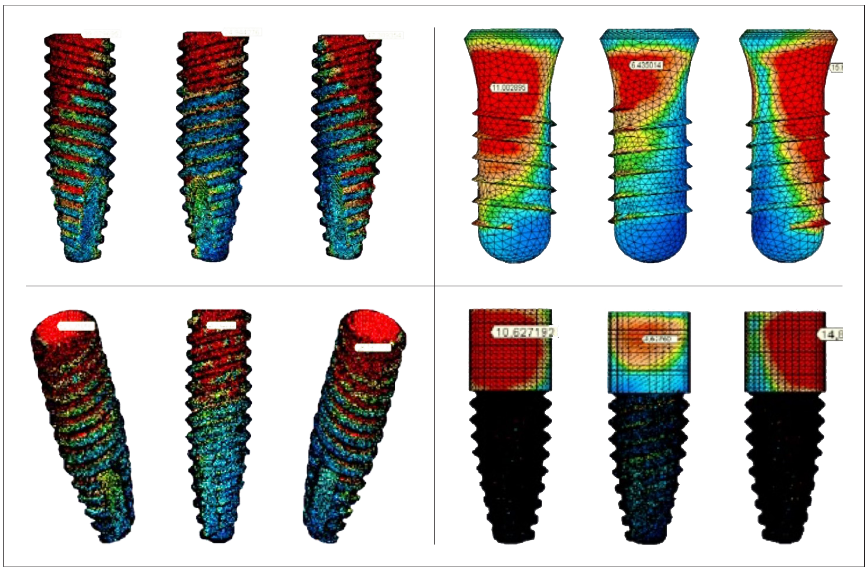

Fig. 11A-11D

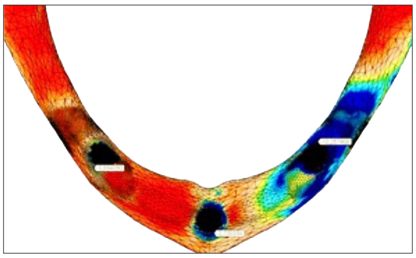

Fig. 10C

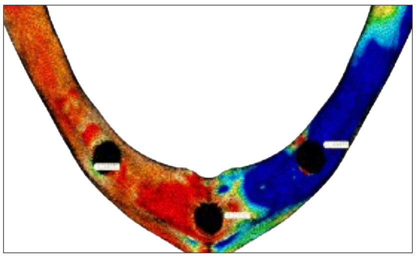

Fig. 10D

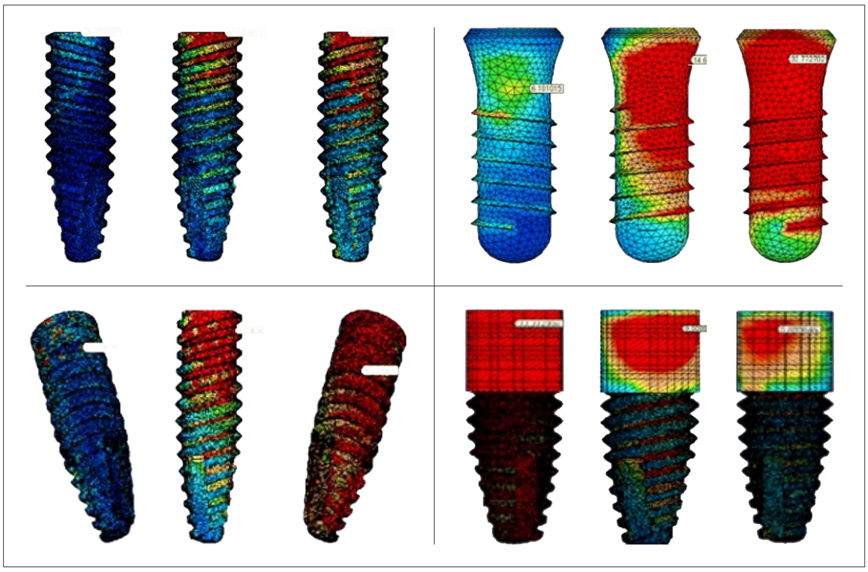

Fig. 12A-12D

Fig. 10A-10D
Maximum tensile stresses in the trabecular bone under posterior (molar) loading across all models.

Fig. 11A-11D
von Mises stresses in the implants under anterior (canine) loading, with peak values localized at the implant nearest to the applied load.

Fig. 12A-12D
von Mises stresses in the implants under posterior (molar) loading, highlighting stress distribution across bone-level and tissue-level configurations.

investigated the biomechanical impact of masticatory forces on fixed prostheses with distal cantilever extensions supported by three implants in the interforaminal region. Finite element analysis, a computational method widely applied in biomedical sciences, enables precise visualization of stress distributions under conditions that are difficult or impossible to reproduce in clinical or laboratory settings. Within implant dentistry, it has become a critical tool for predicting how occlusal loads affect both implants and surrounding bone. Excessive or imbalanced forces during chewing, clenching, or parafunctional activities can accelerate peri-implant bone resorption, compromise osseointegration, and increase the risk of fractures, screw loosening, or prosthetic failures. By simulating these conditions with reproducibility and accuracy, finite element analysis provides insights that inform implant selection, prosthesis design, and clinical decision-making, ultimately contributing to safer, more predictable, and longer-lasting rehabilitations (17, 18).

Posterior mandibular bone resorption is a common limitation during implant planning in edentulous patients. Augmentation procedures, such as lateralization of the inferior alveolar nerve or guided bone regeneration, are frequently employed to enable posterior implant placement (19). However, these interventions are associated with increased morbidity, treatment cost, surgical time, and risk of complications. Consequently, the anterior mandible, particularly the interforaminal region, has been widely utilized due to its relatively preserved bone volume and favorable healing potential (7, 8). Prosthetic designs incorporating cantilever extensions are often used to compensate for the lack of posterior support.

Despite their clinical effectiveness, the incorporation of distal cantilever extensions introduces important biomechanical challenges. Previous finite element studies have confirmed that cantilevers supported by interforaminal implants increase stress on both implants and prosthetic components, thereby elevating the risk of mechanical complications (20). Thus, although full-arch prostheses with distal cantilevers have demonstrated predictable success, their use remains closely associated with higher biomechanical risks (10, 12, 13). Numerous studies have reported that longer cantilevers correlate with greater peri-implant bone loss, higher rates of technical complications, and increased risk of implant failure. Kim et al. (21) reported significantly greater marginal bone loss in patients with cantilevered fixed prostheses, while Halg et al. (22) observed a higher incidence of prosthetic screw loosening and veneering fractures in similar cases. Collectively, these findings highlight that cantilever extensions should be employed with caution, and their length carefully minimized to reduce unfavorable loading patterns and prevent mechanical and biological complications.

The growing clinical reliance on reduced-implant protocols has reshaped treatment planning for edentulous mandibles. Whereas six or more implants were once considered the gold standard, several reports now document the feasibility of restoring the mandible with as few as three implants. A landmark innovation in this context was the Brånemark Novum concept, which involved placing three implants in the anterior mandible and immediately delivering a fixed prosthesis supported by a prefabricated titanium bar (4, 5). This approach demonstrated encouraging short- and mid-term success rates, establishing the feasibility of full-arch rehabilitation with a reduced number of implants. Hatano et al. (23) and Gualini et al. (6) later confirmed the predictability of this approach with standard implant systems, further validating the clinical applicability of the three-implant strategy under controlled biomechanical conditions.

Building on these favorable outcomes, Nobel Biocare modernized the original protocol and reintroduced it as the Nobel Trefoil™ system. This updated approach retained the principle of three interforaminal implants but incorporated design innovations such as implants with a wide 5.0 mm diameter and a polished 4.5 mm transmucosal collar, combined with a prefabricated titanium framework to enable immediate loading on the day of surgery (24). In the present study, this concept was represented by the TRF model, which consistently demonstrated the lowest stress concentrations across cortical bone, trabecular bone, and implant components. These favorable biomechanical results can be attributed to the dimensional advantages of the system, as the wide-diameter tissue-level implants facilitated broader load distribution, thereby reducing localized stress. This is consistent with the findings of Anitua and Orive (25), who reported that increasing implant diameter from 4.0 mm to 5.0 mm reduced peri-implant bone stress by nearly 30%. Nevertheless, the placement of wide-diameter implants requires adequate horizontal bone volume, and in cases of advanced ridge atrophy, grafting procedures may be necessary, limiting the universal applicability of this approach.

Another treatment strategy that has emerged for the rehabilitation of the completely edentulous mandible with three implants is the All-on-3 concept, developed by Oliva et al. (26). This technique extends the principles of the widely adopted All-on-4 approach by positioning one central implant vertically and two posterior implants with distal angulation to optimize anterior bone engagement. Clinical reports have suggested favorable outcomes: Oliva et al. (26) documented a 100% implant survival rate after five years, while Ayna et al. (9) reported no implant failures and an average marginal bone loss of only 1.0 ± 1.0 mm after six years of follow-up. Despite encouraging clinical reports, the present analysis demonstrated that the ALL3 configuration generated substantially higher stresses under nearly all conditions, a finding consistent with previous finite element analyses showing that distal tilting in All-on-4 concepts favors stress distribution (27). In particular, the bone-level implants in this configuration were associated with pronounced stress concentrations in the cortical bone and implant fixtures, indicating potential biomechanical disadvantages that may jeopardize long-term stability.

The literature presents divergent perspectives regarding the adequacy of using only three implants for the rehabilitation of the completely edentulous mandible. Several investigators argue that three implants may not achieve survival rates comparable to protocols involving a greater number of implants, and they advocate for the use of four or more implants to enhance clinical predictability. Heydecke et al. (28) conducted a systematic review and reported that implant-supported fixed full-arch prostheses supported by four to six implants consistently achieved predictable five-year survival rates, thereby establishing this approach as a well-documented treatment option. However, they emphasized that the long-term reliability of three-implant protocols remains uncertain. Similarly, Correa et al. (29) concluded that prostheses supported by three implants provide insufficient resistance against occlusal loads, while four implants offered more favorable mechanical support. In the same context, Simamoto Junior et al. (30) demonstrated that reducing the number of implants in the interforaminal region of an atrophic mandible increased peri-implant stress, suggesting that rehabilitation with four or five implants reduces the risk of biomechanical complications. Consistent with these findings, Fazi et al. (31) reported that prostheses supported by three parallel implants generated significantly higher stress concentrations in both the implants and the surrounding bone compared with four-implant configurations.

Our findings are consistent with previous finite element investigations demonstrating that the Trefoil concept provides the most balanced stress distribution, whereas the All-on-3 design produces the highest and least favorable stresses (32). Taken together, these results highlight that implant macrodesign and placement geometry—rather than merely increasing the number of implants—are decisive determinants of biomechanical performance. The present analysis adds to this evidence by directly comparing stress distribution across three-implant rehabilitation models. Among the tested designs, the Trefoil (TRF) configuration, which incorporates wide-diameter tissue-level implants, consistently exhibited the most favorable load distribution in both bone and implant structures. By contrast, the All-on-3 (ALL3) model, characterized by posteriorly tilted implants, generated the highest stress concentrations under functional loading. This observation aligns with earlier finite element studies, which likewise reported that tilted implants, although performing adequately under vertical loads, tend to transmit unfavorable stresses under oblique functional forces (33). When conventional vertical strategies were examined, the three tissue-level implant (3TL) configuration demonstrated more favorable stress distribution than the three bone-level implant (3BL) design, underscoring the biomechanical advantages of tissue-level systems. In the present analysis, tissue-level implants consistently reduced peri-implant stresses and promoted more homogeneous load transfer. Nevertheless, not all studies concur. For example, a finite element analysis investigating implant macrodesign in mandibular overdentures reported that tissue-level implants increased stresses within surrounding cortical bone compared to bone-level designs, despite reducing stress concentrations within the implant body itself (34). This apparent divergence underscores the complex interplay among implant design, collar geometry, and clinical indication, suggesting that the biomechanical behavior of tissue-level implants may differ depending on whether they are employed in overdenture protocols or in full-arch fixed rehabilitations with distal cantilever extensions.

Collectively, these findings highlight the clinical value of tissue-level implants in three-implant rehabilitation of the edentulous mandible. The consistent performance of the TRF and 3TL models emphasizes the capacity of this implant type to attenuate stress transmission to peri-implant bone and prosthetic components. Reduced stress concentrations associated with tissue-level implants may play a critical role in preserving marginal bone levels and enhancing long-term stability. Supporting this interpretation, Kim et al. (21) demonstrated that tissue-level connections generated nearly 50% lower peri-implant stresses than bone-level designs, primarily due to their transmucosal collar reducing crown height and modifying load transfer dynamics. These results strongly suggest that tissue-level implants provide distinct biomechanical advantages in three-implant mandibular rehabilitations. Furthermore, in agreement with earlier finite element analyses indicating that three interforaminal implants alone are biomechanically insufficient (16), the present study reinforces the necessity of carefully optimizing implant type and configuration to minimize stress concentrations in edentulous mandibular rehabilitations. This emphasizes the importance of meticulous case selection and individualized treatment planning when restoring the completely edentulous mandible with three implants and cantilever extensions. Critical parameters—including implant type, diameter, angulation, and prosthetic framework design—must be selected with precision to ensure favorable stress distribution and compatibility with each patient's anatomical and functional conditions. A tailored, patient-centered approach is essential to mitigate biomechanical risks, preserve peri-implant bone health, and ultimately enhance the long-term success and predictability of prosthetic rehabilitations.

Study limitations

This investigation is limited by its finite element analysis design. While finite element analysis provides valuable insights into biomechanical behavior, it cannot fully replicate the biological variability of bone quality, healing dynamics, or patient-specific functional factors. Static loading conditions were applied to simulate masticatory forces; however, these do not reflect the complex, cyclic, multidirectional, and time-dependent nature of intraoral function. In addition, material properties were modeled as homogeneous, isotropic, and linearly elastic, which may not accurately represent the true biomechanical characteristics of bone and prosthetic components. Consequently, the results of this study should be regarded as theoretical predictions rather than direct clinical outcomes. Future research should include in vivo experiments and long-term clinical trials to validate these findings and to translate the biomechanical insights into evidence-based guidelines for the rehabilitation of the edentulous mandible with three implant-supported prostheses.

CONCLUSION

Within the limitations of this finite element analysis,

the Trefoil (TRF) configuration demonstrated the most favorable biomechanical performance, consistently producing the lowest stress concentrations in both peri-implant bone and implant components. Nevertheless, its clinical application requires sufficient bone volume to accommodate wide-diameter implants, which may restrict its use in cases of advanced alveolar resorption. By contrast, the All-on-3 configuration, characterized by angled posterior implants, generated the highest stress levels across cortical bone, trabecular bone, and implant structures, suggesting potential biomechanical disadvantages that could compromise long-term stability.
These results indicate that vertically placed tissue-level implants provide biomechanical advantages for three-implant-supported fixed restorations of the completely edentulous mandible. Careful case selection, based on anatomical conditions and functional demands, remains essential to optimize outcomes. Long-term prospective clinical studies are required to validate these biomechanical findings and to determine their implications for treatment predictability and patient-centered success.

Mandatory Declarations

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Conflict of Interest
The authors declare no conflicts of interest related to the research, authorship, or publication of this article.

Ethical Approval
Not applicable. This study was conducted entirely through computer-based finite element simulations. The cone-beam computed tomography dataset used to construct the virtual model was fully anonymized, and all patient identifiers were removed.

Author Contributions
Sercan Küçükkurt was responsible for conceptualization, funding acquisition, project administration, supervision, software, and validation. Data curation, investigation, methodology, and resources were carried out jointly by Sercan Küçükkurt, Sena Bayraktar, and Hasan Çağrı Kobak. Formal analysis and visualization were performed by Sena Bayraktar and Hasan Çağrı Kobak. The original draft of the manuscript was prepared by Sena Bayraktar and Hasan Çağrı Kobak, while review and editing were undertaken by Sercan Küçükkurt.

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