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Original Article
(Protocol Development)

Dentistry Section

Protocol Development for Virtual CAD/CAM Surgical Guides in Non Restorable Single Tooth Implant Rehabilitation: A Computational Simulation Study

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ABSTRACT

Introduction: Accurate implant positioning in single non restorable tooth rehabilitation is critical due to limited anatomical space and sensitivity to angular deviation. Virtual Computer-aided Design (CAD)/Computer-aided Manufacturing (CAM) surgical guides improve drilling control; however, their mechanical stability depends strongly on guide design and stabilisation strategy. Developing a structured protocol that integrates mechanical validation within digital guide fabrication remains essential for predictable guided implant placement.

Aim: To develop and computationally evaluate a virtual CAD/CAM protocol for tooth-specific surgical guides incorporating bend-plate reinforcement for improved stability in single-tooth implant rehabilitation.

Materials and Methods: This computational simulation study was conducted at the Department of Mechanical Engineering, G H Raisoni College of Engineering, Nagpur, Maharashtra, India, over a period of six months, from June 2025 to November 2025. Cone Beam Computed Tomography (CBCT)-derived anatomical data were processed using Medical Information Mart for Intensive Care (MIMICS) and 3-Matic software to design three guide geometries: pilot-drill, complete-drill and palatal-supported guides. Each geometry was evaluated under three stabilisation strategies tooth-supported, anchor-pin-assisted and bend-plate-assisted resulting in nine biomechanical configurations. Finite Element Analysis (FEA) assessed deformation, Von-Mises stress and Factor Of Safety (FOS) under simulated drilling loads. Virtual implant positioning deviation was quantified using coronal, apical, angular and depth error metrics. Comparative numerical analysis was performed.

Results: Progressive improvement in mechanical stability was observed from tooth-supported to anchor-pin and bend-plate-assisted configurations across all guide designs. Bend-plate-reinforced guides demonstrated the lowest deformation and stress responses with higher safety margins, while the palatal-supported bend-plate design exhibited the most favourable biomechanical performance. Virtual deviation analysis showed corresponding reductions in implant positional errors, indicating enhanced trajectory control with increased stabilisation.

Conclusion: The proposed virtual CAD/CAM protocol successfully integrates bend-plate reinforcement into tooth-specific surgical guides, resulting in improved mechanical rigidity and predictive implant positioning accuracy. This framework provides a scalable foundation for future experimental validation and clinical translation in guided implant surgery.

Keywords: Bend plate, Computer-aided design, Computer-aided manufacturing, Tooth-specific surgical guide, Virtual fabrication

INTRODUCTION

Single-tooth replacement has gradually shifted from freehand implant placement toward more controlled, digitally guided approaches. Despite improvements in imaging and planning software, implant positioning in a narrow edentulous space still presents several practical challenges for clinicians. Limited visibility, anatomical constraints and variations in bone morphology can all influence the final drill path and even small angular deviations may affect prosthetic alignment or primary stability. As a result, the accuracy of the initial osteotomy has become a critical factor in achieving predictable outcomes.

Tooth-specific surgical guides have emerged as an appealing option in these situations because they rely on the adjacent teeth for support rather than soft-tissue or extensive anatomical surfaces. This localised anchorage can provide a stable reference for drilling, especially in single non restorable tooth cases where the edentulous span is minimal [1]. However, because these guides depend heavily on their design geometry, minor differences in shape, thickness, or supporting structures can significantly alter how well the guide performs during surgery. Many of the designs found in current literature offer useful principles, but there is still limited discussion on how to systematically create and modify such guides in a virtual environment.

Digital planning software, including MIMICS software, now allows clinicians and engineers to work with CBCT-derived anatomical models in considerable detail [2]. This opens the door for more refined customisation of surgical guides and the ability to experiment with different support mechanisms before committing to a manufactured model. One such design element, the bend plate, has potential to increase the rigidity and seating accuracy of the guide, yet its integration into tooth-supported guides has not been fully explored. Incorporating such features virtually also lets the designer assess whether the geometry interferes with access, sleeve positioning, or the planned drilling trajectory [3].

Accordingly, this work presents a computational and in-vitro protocol development framework for virtual CAD/CAM surgical guides designs intended for single non restorable tooth replacement. These include a pilot-drill guide, a complete-drill guide and a palatal-supported variant, each incorporating a bend-plate structure for additional stabilisation. Physical prototypes of all three guide variations were 3D printed using PLA to evaluate fit and manufacturability and FEA was conducted to assess deformation, Von-Mises stress and FOS under simulated drilling conditions. By presenting the workflow in a systematic manner, this paper provides a foundation that can be expanded in future studies involving clinical application.

Key technical developments: The development of tooth-specific surgical guides for single non restorable tooth replacement has progressed considerably with the wider use of CBCT imaging and advanced segmentation tools [4]. However, most existing designs still follow a standard template that focuses on a simple sleeve holder supported by the adjacent teeth. While functional in many cases, such conventional models often lack the structural reinforcement needed when drilling forces are high or when the operator requires a more controlled angulation path. The present work introduces several technical refinements within a virtual design environment that address these limitations [5].

One of the central advancements in the present study is the incorporation of a bend-plate stabilisation structure. Unlike bulkier external supports or multi-sleeve extensions, the bend plate offers a compact reinforcement that can be integrated into the guide body without obstructing the working field. Its curved geometry is designed to distribute drill-induced forces across a wider surface area, reducing the risk of micro-movement during osteotomy preparation. Integrating this feature at the virtual design stage allows the designer to make precise adjustments in plate thickness, curvature and contact points before any physical prototype is manufactured [6].

Another important development is the differentiation of three distinct guide configurations, each addressing a specific clinical need. The pilot-drill guide represents the most conservative design, offering a controlled starting point for osteotomy preparation while maintaining minimal bulk. This version is particularly useful when space around the adjacent teeth is limited or when the clinician prefers to complete the remaining drilling freehand [7]. The complete-drill guide, in contrast, includes a full-length sleeve structure meant to guide multiple drill diameters. In the digital environment, this required careful calibration of sleeve dimensions and alignment to ensure that the bend plate did not interfere with the drill path. The third design, a palatal-supported guide, extends its anchorage beyond the immediate tooth surfaces to engage the palatal region, providing a more stable seating platform for cases requiring higher resistance to rotational forces [8].

These distinctions were made possible by the flexibility of the virtual modelling workflow. Working within MIMICS software allowed for fine control over segmentation thresholds, guide thickness, offset parameters and drill-path simulations [9]. The ability to manipulate the drill trajectory interactively made it possible to refine each design to suit its intended purpose, rather than relying on a one-size-fits-all guide geometry. This approach enables a more tailored design strategy that can later be adapted to patient-specific cases once 3D printing and in-vitro validation are considered.

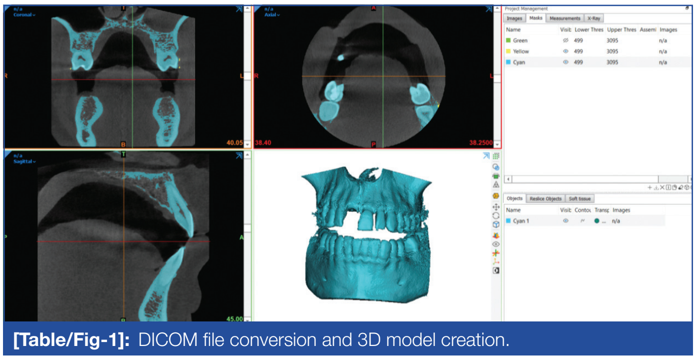
Together, these technical developments demonstrate that virtual guide fabrication can extend beyond basic modelling and move toward more mechanically informed and clinically adaptable structures. The bend plate, the three design variations and the iterative digital workflow collectively represent meaningful steps toward improving the reliability and customisation potential of tooth-specific surgical guides [10].

MATERIALS AND METHODS

The present study was designed as a computational simulation study focusing on virtual fabrication and mechanical evaluation of tooth-specific surgical guides for single non restorable tooth implant rehabilitation. The work was conducted at the Department of Mechanical Engineering, G H Raisoni College of Engineering, Nagpur, Maharashtra, India, over a period of six months, from June 2025 to November 2025. CBCT scan data (DICOM format) were anonymised and processed using MIMICS and 3-Matic software to generate three-dimensional jaw and guide models. Implant planning and trajectory assessment were performed using Implastation, followed by mechanical evaluation through Ansys Discovery FEA. Prototype validation was carried out using PLA-based 3D printed models. As the study involved computational modelling and virtual analysis without human intervention, ethical committee approval was not required as per institutional guidelines.

Study Procedure

Imaging data and segmentation: A CBCT scan of a representative single-tooth edentulous site was used as the starting point. The DICOM files were imported into MIMICS software, where segmentation was performed to isolate the maxillary or mandibular arch from surrounding soft-tissue and air spaces as shown in [Table/Fig-1]. The selected CBCT dataset represented a typical single-tooth edentulous site with adequate alveolar ridge width and height for standard implant placement, absence of pathological defects and intact adjacent teeth providing stable support surfaces for guide seating. This configuration reflects a commonly encountered clinical scenario in single-tooth implant rehabilitation. Hard-tissue segmentation was performed using grayscale threshold ranges corresponding to mineralised structures, typically between 499 and 3095 HU, followed by manual refinement using region-growing and slice editing to ensure accurate delineation of enamel and cortical bone boundaries. Thresholding values were adjusted manually to ensure that the enamel, dentin and cortical bone were captured accurately. Additional corrections, such as region growing and slice-by-slice editing, were carried out to obtain a clean 3D model of the dentoalveolar structure [11].



Name	Visit	Lower Thres	Upper Thres	Asseml	Images
Green		499	3095		n/a
Yellow		499	3095		n/a
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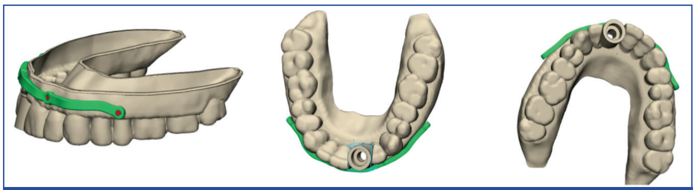
[Table/Fig-1]: DICOM file conversion and 3D model creation.

Creation of the anatomical model: After segmentation, the 3D mask was converted into a surface mesh. Artifacts and irregularities were smoothed using the built-in mesh-editing tools, while care was taken not to distort critical anatomical landmarks. The missing-tooth region was examined from multiple angles to determine the optimal insertion path for a standard implant, forming the basis for the guide's drill trajectory [12].

Definition of implant axis and drill path: The proposed implant axis was mapped using the planning tools within the software. Orientation was established by accounting for bone availability, prosthetic alignment and the expected emergence profile. A standard cylindrical threaded implant model with a diameter of approximately 3.5-4.0 mm and length of 10-11 mm was virtually positioned, reflecting commonly used dimensions for single-tooth replacement in the selected anatomical region. The reference implant axis was determined based on available bone volume, alignment with the prosthetic emergence profile and avoidance of cortical plate perforation, using cross-sectional CBCT evaluation to ensure central positioning within the alveolar ridge. Guide sleeves were modelled with an inner diameter matching the pilot and drilling instruments (approximately 2.0-2.2 mm for pilot drills) and an outer diameter of 4.0-5.0 mm to provide sufficient structural strength and guide stability. The bend plate was designed with a thickness of approximately 1.0-1.5 mm and a gentle curvature radius adapted to the buccal surface contour to optimise contact area while minimising bulk. Material properties were assigned consistent with biocompatible surgical guide resin in the FEA model. Clearance and contact adaptation were assessed using digital distance measurement tools within the CAD environment. A tolerance range of approximately 0.1-0.3 mm was maintained between guide surfaces and adjacent anatomical structures to ensure passive seating without interference. The drill path was modelled as a cylindrical volume that extended coronally through the future guide and apically into the bone. This virtual cylinder served as a reference for positioning the guide sleeves in all three design variants [13].

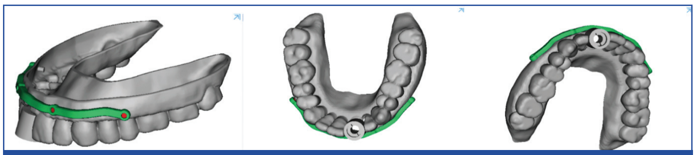
Design of three surgical guide variants: Three distinct surgical guides were developed around the same anatomical model and drill path:

- **Pilot-drill guide with bend plate:** A minimal guide body was shaped to rest on the adjacent teeth. A short pilot sleeve was added to control the initial osteotomy. The bend-plate structure was integrated along the buccal side to increase lateral stability without obstructing access [Table/Fig-2].



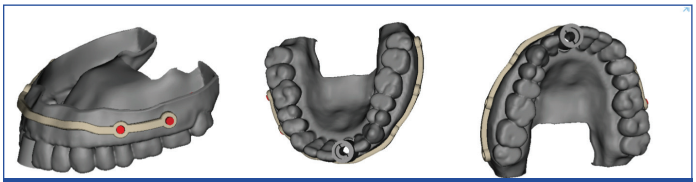
[Table/Fig-2]: Pilot-drill guide with bend plate.
Three representative views of the pilot-drill surgical guide showing the buccal bend plate, the pilot sleeve position and the tooth-supported seating surface. The compact design and minimal footprint are visible in all orientations, highlighting the simplified geometry intended for initial osteotomy control

- **Complete-drill guide with bend plate:** This design incorporated a longer sleeve intended to guide multiple drilling steps. Additional material thickness was added around the sleeve for strength. The bend plate was modified to fit the larger geometry and maintain a firm seating surface [Table/Fig-3].



[Table/Fig-3]: Complete-drill guide with bend plate.
Multi-view representation of the complete-drill guide featuring the extended sleeve channel and reinforced bend-plate structure. The images show how the longer drilling pathway influences guide thickness, clearance and the interaction between the sleeve and adjacent teeth

- **Palatal-supported guide with bend plate:** For cases requiring enhanced anti-rotation resistance, the guide was extended toward the palatal region. This provided a broader contact area and the bend plate was positioned to complement the expanded footprint. The guides were shaped using a combination of Boolean operations, offset surfaces and manual contour adjustments [Table/Fig-4].



[Table/Fig-4]: Palatal-supported guide with bend plate.
Three views of the palatal-supported guide illustrating the extended palatal contact area, enhanced seating stability and integration of the bend plate. The broader base and anti-rotation support are clearly visible in each perspective

- **Digital evaluation of fit and geometry:** Each guide was assessed in the virtual model for adaptation to tooth surfaces, path of insertion, sleeve-trajectory alignment, clearance around adjacent teeth, potential interference between the bend plate and the drill path. The evaluation relied on visual inspection, distance measurements and trial positioning within the software.

Finite Element Analysis (FEA): The FEA was performed to evaluate the mechanical response of the three guide configurations under simulated drilling load. The nine surgical guide configurations evaluated in this study were intentionally developed to represent a structured combination of three clinically relevant guide geometries pilot-drill as shown in [Table/Fig-2], complete-drill as shown in [Table/Fig-3] and palatal-supported as shown in [Table/Fig-4] designs with three commonly used stabilisation strategies tooth-supported seating, anchor-pin fixation and bend-plate reinforcement. This matrix-based design approach allowed systematic assessment of how both guide architecture and support mechanism independently and collectively influence mechanical behaviour and trajectory control. By exploring all nine combinations within a unified protocol, the study provides a comprehensive framework for optimising guide design rather than relying on a single configuration. To investigate the effect of stabilisation strategy on the mechanical behaviour of surgical guides, three distinct support conditions were considered for the proposed stabilisation structure. For each of the three guide variants support conditions were modelled, resulting in a total of nine biomechanical scenarios for comparative finite element evaluation. The jaw model and guide geometries were imported into ANSYS, material properties were assigned assuming standard biocompatible resin (E=2900 MPa, ν=0.3) for guide fabrication and a cortical-cancellous bone interface was considered for the mandibular segment. The jaw base was constrained as a fixed support, while a drilling load of 150 N was applied along the implant axis at the sleeve hole, replicating peak axial drilling force during osteotomy preparation [14]. Mesh refinement was carried out in high-stress regions including the sleeve-guide interface and bend-plate joint to ensure convergence. The geometries were discretised using tetrahedral solid elements with localised mesh refinement applied in high-stress regions, particularly around the guide sleeve interface and bend-plate junction. A mesh convergence study was conducted by progressively refining element size until variations in peak Von-Mises stress and total deformation remained within 5%, ensuring numerical stability of the results. The final models contained approximately 300,000 to 550,000 elements depending on guide configuration. The output parameters extracted included total deformation, Von-Mises stress and FOS, enabling quantitative comparison between all nine design variations. For prototype fabrication, PLA filament was used for 3D printing to validate physical form and assembly fit, acknowledging that final clinical manufacturing would employ biocompatible surgical resin or reinforced resin, titanium materials instead [15,16].

STATISTICAL ANALYSIS

Quantitative outputs obtained from FEA (deformation, Von-Mises stress and FOS) and virtual implant deviation metrics were tabulated for all nine guide configurations. Descriptive statistics were calculated for each parameter. Comparative evaluation among stabilisation strategies was performed using non parametric statistical testing (Kruskal-Wallis test), followed by pair-wise post-hoc comparisons where applicable. A significance level of $p<0.05$ was considered statistically significant. Statistical analysis was performed using standard scientific data analysis software.

RESULTS

The three surgical guide designs were successfully created within the virtual modelling environment and each demonstrated distinct characteristics based on its intended function and supporting geometry. Although all designs were built around the same anatomical model and planned implant axis, their seating behaviour, sleeve positioning and interaction with the bend-plate structure varied noticeably [Table/Fig-5].

Pilot-drill guide with bend plate: The pilot-drill design produced the smallest overall footprint. It seated predictably on the adjacent

Feature	Pilot-drill guide with bend plate	Complete-drill guide with bend plate	Palatal-supported guide with bend plate
Primary purpose	To guide the initial pilot osteotomy with minimal bulk	To control full drilling sequence with maximum sleeve stability	To enhance seating stability through extended palatal support
Guide footprint	Smallest; limited to adjacent teeth	Moderate; slightly bulkier due to longer sleeve	Largest; extends into the palatal region for added anchorage
Sleeve type	Short pilot sleeve	Full-length multi-step sleeve	Full-length sleeve with extended support base
Stability level (virtual assessment)	Good for basic angulation control	Higher stability for controlled sequential drilling	Highest rotational and seating stability due to extended contact area
Bend-plate integration	Easy integration: minimal adjustments needed	Requires careful adjustment to avoid sleeve interference	Smooth integration with more available surface area
Space requirements	Ideal for limited interproximal space	Requires moderate clearance around adjacent teeth	Best suited for wide palatal spaces; may not fit tight arches
Expected clinical use case	Experienced operators who need initial guidance only	Cases demanding precise angulation throughout drilling	Situations needing maximum guide rigidity and anti-rotation
Visualisation and access	Excellent visibility; minimal obstruction	Moderate; full sleeve reduces visibility	Slightly reduced buccal view due to extended support
Design complexity	Simplest to design; fast to model	Intermediate complexity	Most complex; requires careful contouring

[Table/Fig-5]: Comparison of the three tooth-specific surgical guide designs.

teeth, with minimal extension into surrounding regions. The short pilot sleeve aligned well with the planned trajectory and did not obstruct visibility during virtual inspection. The bend plate reinforced the buccal aspect of the guide without affecting the path of insertion. This configuration showed the least amount of interference and required minimal contour correction.

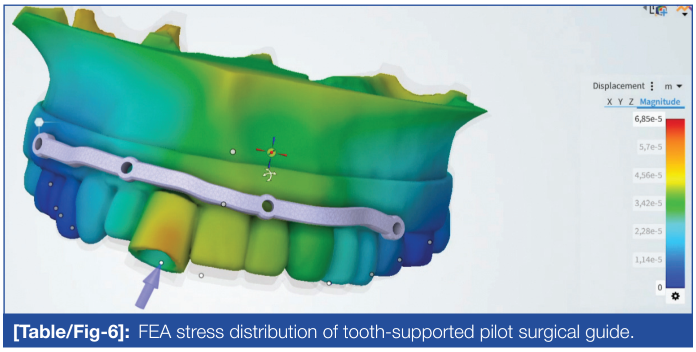
Complete-drill guide with bend plate: The full-sleeve model resulted in a bulkier guide due to the increased material surrounding the longer drilling channel. Despite this, the guide maintained a stable seating pattern on the tooth surfaces. The bend plate had to be adjusted more carefully in this design, as the expanded guide body reduced available clearance. Once refined, the plate integrated smoothly and added lateral rigidity. Minor adjustments were needed to avoid contact with the contralateral tooth during insertion.

Palatal-supported guide with bend plate: The palatal-supported variation produced the broadest contact area, extending the guide's anchorage beyond the immediate tooth surfaces. This design appeared the most resistant to rotation within the virtual model. The additional palatal mass allowed the bend plate to be positioned more naturally without competing for space around the sleeve. The extended support also helped stabilise the drill axis visually.

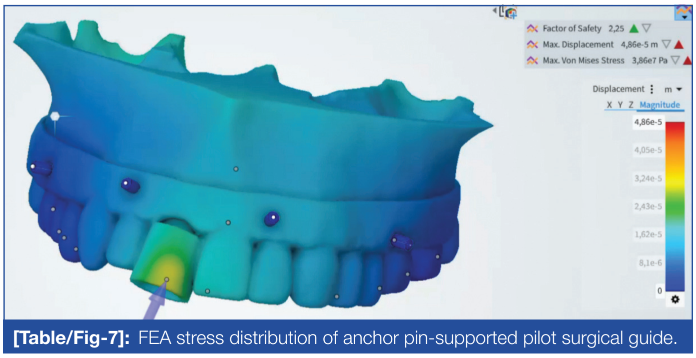
Sleeve alignment and clearance: Across all designs, the planned drill axis remained within acceptable alignment tolerances determined by the virtual reference cylinder. Clearance around the adjacent teeth was adequate and no collisions were observed between the drill path and the bend-plate structure. The palatal-supported guide offered the most generous clearance, while the complete-drill guide had the narrowest margins.

Virtual fit and adaptation: All three models exhibited smooth adaptation to the segmented enamel surfaces, with no visible gaps in the contact regions. The path of insertion for each design was achievable without rotation or excessive tilting. The digital fit assessment did not reveal any anomalies that would prevent physical fabrication.

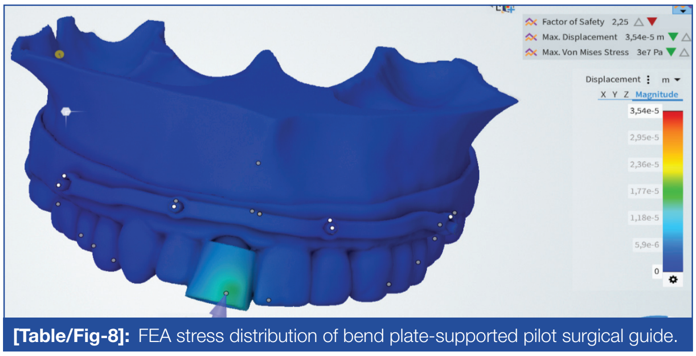
FEA results: The FEA results demonstrated a clear reduction in deformation and stress when additional stabilisation was introduced. Comparative numerical evaluation was performed across all nine guide configurations using deformation, Von-Mises stress and FOS values obtained from FEA [Table/Fig-6-15]. [Table/Fig-8] shows FEA stress distribution of Bend Plate-Supported Pilot Surgical Guide; [Table/Fig-11] shows FEA stress distribution of bend plate-supported complete surgical guide and [Table/Fig-14]. Shows FEA stress distribution of bend plate-supported palatal surgical guide. Tooth-supported guides showed the highest displacement and stress values, whereas anchor-pin support significantly improved rigidity. The best performance was observed in bend-plate reinforced guides,



[Table/Fig-6]: FEA stress distribution of tooth-supported pilot surgical guide.



[Table/Fig-7]: FEA stress distribution of anchor pin-supported pilot surgical guide.



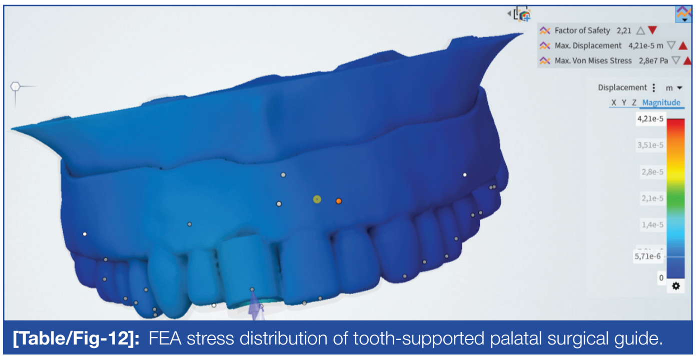
[Table/Fig-8]: FEA stress distribution of bend plate-supported pilot surgical guide.

[Table/Fig-9]: FEA stress distribution of tooth-supported complete surgical guide.

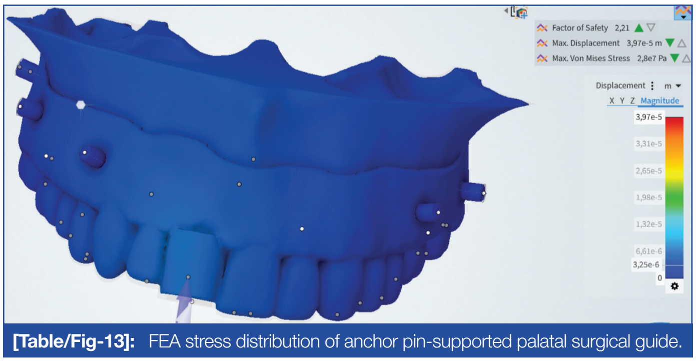
which exhibited the lowest deformation and stress distribution and higher FOS values in all configurations. Palatal-supported bend-plate design recorded the most favourable response, indicating improved resistance to drilling-induced forces and reduced risk of micromotion during osteotomy drilling. The complete quantitative findings for all nine models are provided in [Table/Fig-15].

[Table/Fig-10]: FEA stress distribution of anchor pin-supported complete surgical guide.

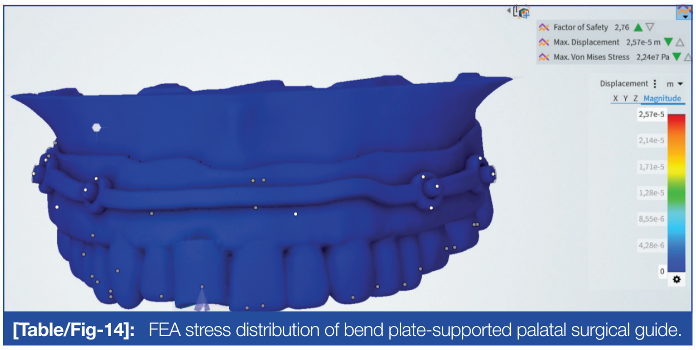
[Table/Fig-11]: FEA stress distribution of bend plate-supported complete surgical guide.



[Table/Fig-12]: FEA stress distribution of tooth-supported palatal surgical guide.



[Table/Fig-13]: FEA stress distribution of anchor pin-supported palatal surgical guide.



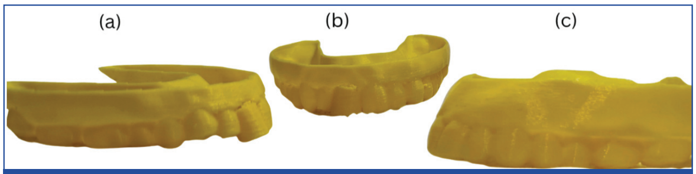
[Table/Fig-14]: FEA stress distribution of bend plate-supported palatal surgical guide.

Design type	Table/Fig	Deformation ($\times 10^{-5}$ m)	Von-Mises stress ($\times 10^{7}$ Pa)	FOS
Tooth supported- pilot	[Table/Fig-6]	6.85	8.09	1.48
Anchor pin- pilot	[Table/Fig-7]	4.86	3.86	2.25
Bend plate- pilot	[Table/Fig-8]	3.54	3.00	2.25
Tooth supported- complete	[Table/Fig-9]	5.46	4.21	1.47
Anchor pin- complete	[Table/Fig-10]	4.53	3.51	1.77
Bend plate- complete	[Table/Fig-11]	3.42	2.99	2.07
Tooth supported- palatal	[Table/Fig-12]	4.21	2.80	2.21
Anchor pin- palatal	[Table/Fig-13]	3.97	2.80	2.21
Bend plate- palatal	[Table/Fig-14]	2.57	2.24	2.76

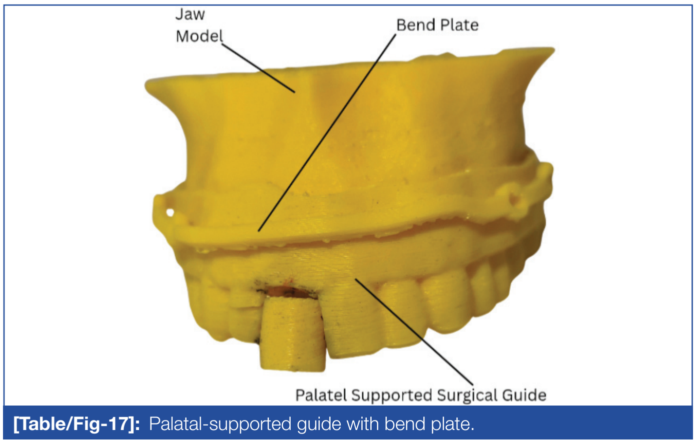
[Table/Fig-15]: FEA results for all nine guide configurations.

The mechanical trend strongly indicates that progressively increasing support contact reduces stress concentration and improves stability. Tooth-supported models rely only on occlusal seating and showed the highest deformation (6.85×10^{-5} m pilot), while anchor-pin fixation reduced deformation due to direct cortical engagement. Incorporation of the bend plate further stabilised the guide by distributing load across a larger surface area, resulting in notably lower stresses (as low as 2.24×10^{7} Pa) and the highest safety margins (FOS up to 2.76). This confirms that bend-plate integration increases lateral rigidity and minimises rotational or translational shift during drilling.

3D-printed models: To complement the digital design and simulation workflow, physical prototypes of the jaw model, surgical guide and bend plate were fabricated using PLA material through Fused Deposition Modelling (FDM) 3D printing as shown in [Table/Fig-16]. The printed models were used to verify geometry, assembly compatibility and spatial integration of the bend plate with the surgical guide and jaw anatomy. Although PLA is not intended for clinical application, these prototypes enabled visual and dimensional confirmation of guide seating, plate positioning and overall design feasibility. The physical models provided additional support to the digital validation by demonstrating the practical implementation of the proposed design prior to fabrication using biocompatible materials. Representative images of the printed jaw model, guide and bend plate assembly are shown in [Table/Fig-17].



[Table/Fig-16]: a) Pilot drill guide; b) Complete drill guide; c) Palatal supported complete guide.



[Table/Fig-17]: Palatal-supported guide with bend plate.

Predictive implant positioning: Virtual implant placement predictivity was evaluated using a two-trajectory deviation method. The planned implant axis generated in Implastation was treated as the reference trajectory. A secondary simulated implant axis was created in MIMICS/3-Matic by applying controlled perturbations within clinically reported deviation limits, including angular tilt (±1$^{-4°}$), coronal/apical entry variation (±0.3^{-1} mm), depth variance (±0.2-0.5 mm) and sleeve tolerance clearance (50-200 μm). The two trajectories were aligned using surface registration and deviation was calculated in four metrics: coronal displacement, apical displacement, angular deviation and depth error. The complete deviation outcomes for all nine guide configurations are presented in [Table/Fig-18]. A progressive accuracy improvement was observed from tooth-supported → anchor-pin → bend-plate models. The palatal bend-plate design demonstrated the highest accuracy, with deviation values reduced to 0.33 mm coronal, 0.57 mm apical, 1.8° angular and 0.17 mm depth, indicating superior control over implant trajectory and minimal micro-movement during drilling.

Design type	Coronal deviation (mm)	Apical deviation (mm)	Angular deviation (°)	Depth error (mm)
Tooth supported- pilot	0.82	1.15	4.1	0.42
Anchor pin- pilot	0.64	0.96	3.1	0.28
Bend plate- pilot	0.48	0.76	2.3	0.22
Tooth supported- complete	0.76	1.08	3.9	0.38
Anchor pin- complete	0.57	0.89	2.8	0.26
Bend plate- complete	0.41	0.69	2.1	0.20
Tooth supported- palatal	0.69	1.02	3.5	0.32
Anchor pin- palatal	0.52	0.83	2.6	0.24
Bend plate- palatal	0.33	0.57	1.8	0.17

[Table/Fig-18]: Implant placement accuracy.

Comparative evaluation among stabilisation strategies was shown in [Table/Fig-19]. While the Kruskal-Wallis analysis denotes that the differences did not reach formal statistical significance (p-value >0.05), a clear descriptive trend of progressive improvement in mechanical stability, lower deformation, and higher safety margins was consistently observed across all bend-plate configurations. This indicates a strong mechanical advantage independent of guide geometry, though limited by sample size.

Parameters	Kruskal-Wallis p-value	Tooth vs Anchor	Tooth vs Bend	Anchor vs Bend
Deformation	0.0509	0.10	0.05	0.10
Von-Mises stress	0.3607	0.20	0.20	1.00
Factor of Safety (FOS)	0.1899	0.10	0.10	0.40

[Table/Fig-19]: Statistical comparison of stabilisation strategies Kruskal-Wallis and post-hoc analysis.

DISCUSSION

The virtual development of tooth-specific surgical guides in the present study highlights how relatively small changes in design geometry can influence the expected performance of a guide during implant placement. Although all three guide variants were created from the same underlying anatomical model and drill axis, their structural differences suggest distinct clinical applications and practical considerations. These results correlate with FEA findings, where lower deformation and stress corresponded to reduced deviation, confirming the mechanical and accuracy advantage of bend-plate-reinforced guides [17-19].

The finite element trends observed in the present study are consistent with previous biomechanical investigations on dental implant surgical guides. Ghionea IG et al., reported reduced deformation and stress in reinforced tooth-supported polymeric surgical guides, highlighting the role of structural stiffness in improving drilling stability [20]. Similarly, Miljanovic D et al., demonstrated that enhanced guide fixation significantly improves load distribution and minimises mechanical displacement during osteotomy preparation [21].

The pilot-drill guide represents the most conservative option and mirrors the type of guide often used when the clinician prefers a blended approach, initially relying on guided drilling but completing the remaining steps freehand [22]. In virtual assessment, this design consistently showed minimal obstruction and a straightforward path of insertion. Its compact form and simple sleeve structure suggest that it may be well suited for situations with limited interproximal space or when the adjacent teeth have irregular contours that make larger guides difficult to seat [23].

The complete-drill guide, by contrast, aims for maximal control over drilling depth and angulation. The increased material thickness and longer sleeve provide a more controlled channel, but they also introduce challenges in maintaining clearance. The digital workflow made these interactions easy to visualise and refine, demonstrating the value of virtual design before fabrication [24]. While this design appears mechanically superior for maintaining the planned trajectory, it may require more precise adjustment during clinical adaptation to ensure that the added bulk does not interfere with soft-tissues or adjacent teeth [25].

An important advantage of the proposed bend-plate-assisted guide system is its parametric and scalable design framework. The plate length, support geometry and sleeve angulation can be systematically modified to accommodate different teeth positions and anatomical conditions. The consistently lower deformation, stress values, higher FOS and reduced virtual implant deviation observed across all bend-plate configurations indicate that the stabilisation concept remains mechanically advantageous independent of guide geometry, suggesting strong potential for broader anatomical applicability [26].

The palatal-supported guide offered a different advantage by extending support beyond the immediate tooth surfaces. This approach has been mentioned in literature for enhancing stability, but its effective integration with a bend plate required careful shaping to avoid interfering with the drill path. In this virtual model, the palatal support made the guide feel more “locked in,” especially in terms of rotational stability. Such a design could be beneficial in cases where buccal bone is thin or where the clinician anticipates higher resistance during initial drilling.

The FEA outcomes align with the proposed mechanical rationale that bend-plate reinforcement acts as an additional stabilising element, reducing flexure and improving structural behaviour under drilling load. The consistent decrease in deformation and stress across pilot, complete and palatal variants demonstrates that the design remains mechanically advantageous regardless of guide architecture. When coupled with the virtual implant deviation results, the correlation between lower deformation and improved accuracy becomes evident, the more stable the guide, the closer the implant remains to the planned trajectory. This strengthens the justification for the bend-plate concept as a viable improvement over conventional tooth-supported systems [27]. The virtual implant deviation analysis further quantified this effect by demonstrating progressive reductions in coronal displacement, apical displacement, angular deviation and depth error from tooth-supported to anchor-pin and bend-plate-assisted guides. The lowest deviation values observed in the bend-plate-supported palatal design indicate enhanced resistance to both rotational and translational movement during simulated drilling. Although these outcomes represent predictive virtual accuracy rather than physical measurements, they provide mechanistic evidence that increased structural rigidity directly improves trajectory control. This relationship between mechanical stability and positional precision is consistent with trends reported in guided implant surgery literature.

While the finite element findings indicate enhanced stiffness and reduced deformation in bend-plate-assisted guides, the observed improvement in lateral rigidity is presently based on computational prediction rather than direct experimental measurement. Physical drilling force testing and in-vitro stability assessment will be required to confirm real-time mechanical behaviour under clinical conditions [28].

Anatomical variability plays a critical role in the mechanical behaviour and clinical performance of surgical guides, particularly in single-tooth implant scenarios where ridge morphology, bone density distribution and adjacent tooth contours can significantly influence guide seating and resistance to drilling forces. Variations in alveolar crest height may alter support contact area, while differences in bone quality can affect load transfer and local deformation. Additionally, interproximal tooth morphology may constrain guide footprint and stabilisation strategy selection. Although the present study demonstrates the protocol using a representative anatomical model, the parametric design framework enables adaptation of guide geometry and bend-plate configuration to accommodate diverse anatomical conditions, supporting broader clinical applicability.

Across all designs, the bend plate proved to be a valuable structural addition. Its curved geometry allowed forces to be distributed over a broader surface area without excessively thickening the guide body. Integrating the bend plate at the virtual stage also helped identify areas where it might unintentionally obstruct access, something that would be more cumbersome to adjust after fabrication.

The present study establishes a computational and design framework for bend-plate-assisted surgical guides, supported by FEA and virtual implant placement accuracy evaluation. As the current validation is based on FEA and virtual deviation assessment, the mechanical and accuracy outcomes represent predictive behaviour rather than direct physical measurement. Future work will extend this protocol to multiple CBCT datasets representing diverse anatomical scenarios with varying ridge heights, bone qualities and tooth morphologies to evaluate generalisability. These studies will be followed by physical drilling validation and clinical translation to confirm performance across patient-specific conditions. Physical validation will be performed using biocompatible 3D-printed surgical resins or titanium-based components, followed by in-vitro drilling experiments on jaw models to quantify implant positioning accuracy under controlled conditions. These studies will include direct measurement of coronal, apical, angular and depth deviations, enabling comparison with the virtual predictions presented in this work. Further investigations will explore optimisation of bend-plate geometry, fixation strategy and material selection to enhance lateral rigidity and minimise micromovement during osteotomy. Ultimately, the proposed workflow will be translated into clinical pilot studies to evaluate surgical usability, accuracy and clinical outcomes, positioning the bend-plate-reinforced guide as a scalable solution for guided implant surgery.

Limitation(s)

While the present study establishes a robust virtual framework, it is not without limitations. The current scope did not include experimental or physical drilling validation to measure actual implant positioning accuracy in an in-vitro or clinical setting, nor did it benchmark the proposed designs against existing commercial systems. Furthermore, practical clinical factors such as sterilisation protocols and cost-benefit analyses were outside the scope of this virtual assessment and remain unaddressed. The present study was conducted using a single representative CBCT-derived anatomical model, which does not capture inter-patient variability in alveolar crest height, bone density, ridge morphology, or adjacent tooth anatomy. With only three data points per group, the statistical power is extremely limited. In addition, mechanical validation was performed through FEA and virtual implant deviation assessment, without physical drilling force experiments or in-vitro accuracy measurement. Therefore, the reported stability and positioning outcomes represent predictive computational behaviour rather than direct experimental or clinical performance. Furthermore, the finite element simulations were conducted using a single set of material properties for the surgical guide and a simplified cortical–cancellous bone model. Variations in bone quality corresponding to clinical classifications (D1-D4), ridge height differences and challenging implant angulations were not explicitly modelled in the present analysis. These factors may influence mechanical response and guide stability and should be incorporated in future computational and experimental investigations.

CONCLUSION(S)

The present study established a structured virtual CAD/CAM protocol for the development of tooth-specific surgical guides for single non restorable tooth implant rehabilitation, integrating digital design, FEA and virtual implant positioning evaluation. Three guide geometries pilot-drill, complete-drill and palatal-supported designs were systematically assessed under tooth-supported, anchor-pin-assisted and bend-plate-assisted stabilisation conditions, resulting in nine biomechanical configurations. FEA demonstrated that guide stabilisation strategy plays a critical role in mechanical performance. Tooth-supported designs exhibited the highest deformation and stress, anchor-pin fixation provided moderate improvement and bend-plate-assisted guides consistently showed the greatest rigidity and safety margins across all guide variants. The palatal-supported bend-plate configuration yielded the most favourable biomechanical response. Virtual implant deviation analysis further supported these findings, indicating improved trajectory control with enhanced structural stabilisation. Overall, the bend-plate reinforcement concept offers an effective and adaptable approach for improving the mechanical stability of tooth-specific surgical guides within a virtual design framework. The proposed protocol provides a scalable foundation for future experimental validation and clinical translation in guided implant surgery.

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