Title:
Comparison of CAD Modeling Approaches in the Design of Custom Dental Abutments

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Introduction:

In modern dental prosthetics, computer-aided design (CAD) technology is essential for the creation of dental restorations [1]. Specialized dental CAD tools, such as ExoCAD and 3Shape, are widely used for designing dental implant abutments due to their tailored interfaces and workflows for dental technicians. However, their specific focus limits adaptability, particularly when modeling complex or unconventional 3D geometries. For custom abutment design, general-purpose engineering CAD tools like SolidWorks and PTC Creo offer an opportunity to address these limitations [8, 10]. Similarly, NURBS-based tools such as Rhinoceros and Blender support curve-driven surface generation, which is relevant for producing anatomical forms in dental prosthetics. Yet, these tools often lack integration with standard dental manufacturing workflows and require advanced user expertise, presenting challenges for adoption in prosthodontics [2, 9]. This study compares dental-specific, engineering-based, and NURBS-based modeling approaches for custom dental abutment design. The analysis is guided by comparison criteria derived from a literature review, aiming to assess advantages and limitations and to inform future improvements or adaptations of CAD tools for prosthodontic applications.

Literature review:

The literature review focused on custom dental abutment design and identified aspects for comparing different CAD modeling approaches. Dental-specific approaches are intended to align with clinical workflows by integrating anatomical data from intraoral scans and offering structured user interfaces. However, their reliance on preconfigured parameters can restrict geometry modification, particularly in complex cases [4, 6].

Studies emphasize that intuitive interfaces in dental-specific CAD approaches are critical for guiding users through defining morphological functionalities, such as angulation and emergence profiles, which are essential for functional and aesthetic adaptation of patient-specific restorations [1], [9]. The structure and modification of the abutment are discussed in relation to its three functional segments: implant connection, transgingival, and prosthesis connection segment [7]. Transitioning from virtual geometry modeling to production also emerges as a significant theme. Compatibility with manufacturing processes depends on file export options, surface continuity, and geometric fidelity [3, 6]. The ability to generate production-ready models with minimal post-processing directly impacts the applicability of digital workflows in clinical practice [8]. Several studies distinguish between guided workflows, designed for standardized procedures, and open-ended environments supporting iterative modeling. While the former facilitates use for less experienced users, the latter demands greater CAD expertise but enables broader adaptation [2, 4, 10]. Understanding how these aspects influence CAD performance is essential for selecting or developing solutions that support prosthodontic workflows.

Methodology:

This study compares three CAD approaches, each with a representative tool. ExoCAD Rijeka 3.1 was used for dental, SolidWorks 2020 for engineering, and Rhinoceros 8 combined with the Grasshopper environment for NURBS-based modeling. All three tools were utilized to design a custom dental abutment for tooth 35, located in the lower-left quadrant, following ISO 3950 standards [5]. While ExoCAD offered predefined dental-specific workflows, the approaches in SolidWorks and Rhinoceros required adaptation to their parametric and surface modeling capabilities, enabling customization through adjustable parameters.

A dental abutment (Fig. 1) serves as the connection between an implant and a visible prosthetic restoration and is composed of three main segments: the implant connection, the transgingival segment adapting to soft tissues, and the prosthesis connection providing support for the prosthetic crown [7].

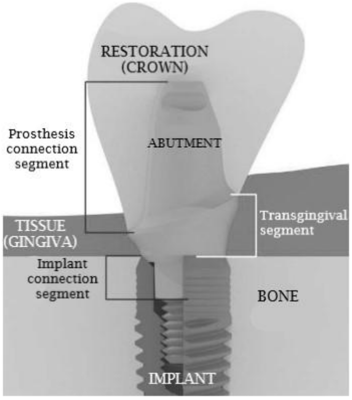

Fig. 1: Implant abutment assembly [7].

Comparison criteria, derived from a literature review, validated by an industrial representative and summarized in Table 1, include parameter management, abutment geometry modification, model preparation for manufacturing, workflow design, and user expertise.

Parameter management assesses the tools' ability to manage design customization, focusing on ease of parameter definition and support for dental-specific functionalities. Geometry modification compares adaptability in altering abutment segments: the implant connection considers compatibility with various implant systems and platform sizes, transgingival adjustments are assessed by soft tissue contouring capabilities, and prosthesis connection focuses on angulation, emergence profile, and crown alignment. Model preparation for manufacturing examines the level of design refinement required before production, including surface continuity, model integrity, and exportable file generation compatible with dental CAD/CAM workflows. Finally, workflow design and user expertise refer to whether the modeling workflow is guided or open-ended and the corresponding expectations regarding dental knowledge and CAD proficiency.

Criteria	Description
C1) Parameter management [1, 4]	Support for controlling design parameters through an interface aligned with dental modeling tasks
C1.1	Intuitiveness of parameter definition and adjustment in dental-specific modeling tasks
C1.2	Availability and integration of dental-specific functionalities
C2) Abutment geometry	The extent to which different aspects of the abutment design can be

modifications [7, 8]	customized, including imposed constraints
C2.1	Modification ability of the implant connection segment, considering tool-imposed constraints and predefined parameters
C2.2	Modification ability of the transgingival segment
C2.3	Modification ability to prosthesis connection segment
C3) Model preparation for manufacturing [3]	Ability to finalize the model for production and assess its adaptability for manufacturing
C3.1	Efficiency of model preparation for manufacturing
C3.2	Compatibility of the final model with manufacturing technologies
C4) Workflow design and user expertise [1, 2]	Adaptability of the design workflow and expertise required for effective use
C4.1	Level of expertise required to understand the dental context
C4.2	Level of expertise required in CAD modeling
C4.3	Adaptability of the workflows (e.g., iterative vs. linear)

Tab. 1: List of comparison criteria for comparing CAD tools.

Results:

This section presents analysis of three distinct CAD approaches to custom abutment design using representative CAD tools—ExoCAD, SolidWorks, and Rhinoceros with Grasshopper—structured according to how each approach supports the given criteria.

ExoCAD integrates dental-specific functionalities via a structured project setup, enabling users to define patient-specific data, restoration type, implant system, and material following a typical sequence of steps common across dental CAD workflows (Fig. 2a). The interface allows limited parameter manipulation: implant positioning is visually guided, while connection geometries are restricted to components available in the library. The transgingival emergence profile is auto-generated from scan data; users can adjust the transition line by moving control points, but vertical placement is restricted to the gingival margin level. Attempts to exceed this boundary are automatically corrected, preventing anatomically unrealistic designs. Adjustments are confined to clinically acceptable limits, with real-time visual feedback. For instance, narrowing below material thickness thresholds is blocked to ensure structural integrity. The prosthesis connection segment is defined by three interlinked control curves. Modifying one curve triggers proportional changes in the others, maintaining geometry and occlusal alignment. These modifications are restricted by predefined manufacturing parameters, such as minimum crown thickness, enforced during editing. Once the geometry definition is finalized, ExoCAD transitions to a manufacturing preparation stage, where orientation, material parameters, and machining allowances are defined. Although toolpath generation is delegated to external CAM software, the model is exported in formats compatible with standard dental production systems. The workflow is predefined and linear, with limited backward editing and restricted editing capability. While advanced control is available through *Expert Mode*, this study remained within the *Wizard Mode* framework to reflect routine clinical conditions.

SolidWorks relies on a parametric approach, in which key dimensions—such as implant connection depth, transgingival height, and prosthesis connection angulation—are defined through global variables and linked through equation-based dependencies (Fig. 2b). No embedded workflow is provided; users are responsible for defining modeling logic, organizing feature dependencies, and integrating anatomical data. The initial model must be manually constructed by the user, using standard CAD operations to define key reference features and geometry structure. Unlike a dental-specific approach, parameter values can be continuously adjusted and recalculated throughout the model. Geometric functionalities are constructed using standard CAD operations, all referenced to the parameter structure. The implant connection is modifiable without predefined constraints. The transgingival segment is modeled through surface construction guided by anatomically defined reference planes, enabling the formation of a controlled concave contour. The prosthesis connection integrates parametric inputs with alignment sketches to accommodate restoration requirements. The model is exported in STL or STEP format, suitable for downstream CAM operations. Although the manufacturing setup is performed externally, the parametric structure ensures geometric integrity across revisions.

Rhinoceros with Grasshopper supports a user-defined script-based modeling process (Fig. 2c). The model is driven by a set of adjustable values, including implant interface dimensions, transgingival profile transitions, and prosthesis connection angulation. These parameters are linked to predefined Grasshopper components that generate geometric features based on user input. For instance, implant connections are typically defined using parametric primitives, such as configurable polygonal bases. Values are modified via number sliders and graph-based mapping functionality, with all dependencies explicitly defined in the script. The implant connection is generated from polygonal primitives, the transgingival profile is shaped using diameter transitions controlled by a graph-based mapping functionality, and the prosthesis connection is built through height and orientation parameters manually aligned to anatomical scan data. Parameter adjustments are immediately visualized in the modeling viewport, facilitating iterative tuning. The model is exported in STL or STEP formats, but CAM preparations such as solid closure, surface continuity checks, and toolpath configuration must be handled externally. Anatomical scans, typically obtained from intraoral scanners or cone-beam computed tomography (CBCT), provide visual references but are not computationally linked to the parametric definitions of geometry, requiring users to manually interpret anatomical landmarks for design adjustments. The modeling process is entirely manual and adaptable; no predefined sequence exists, and the user must structure the design logic to suit clinical objectives. While basic changes can be applied via high-level inputs, deeper modifications require direct script restructuring. This approach demands expertise in visual programming, parametric control, and surface modeling, alongside familiarity with dental anatomical constraints.

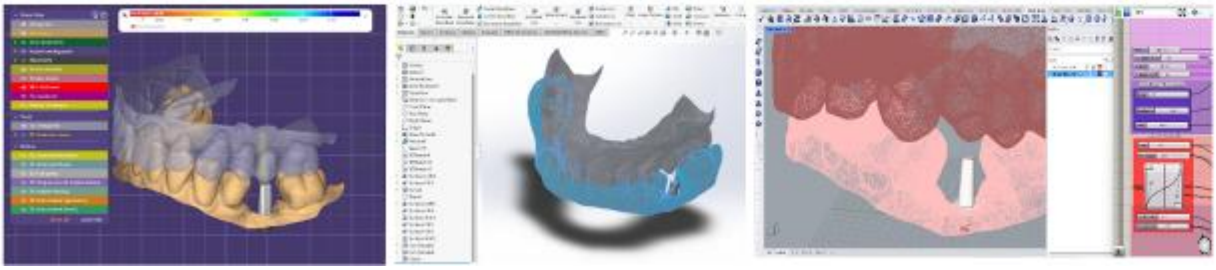

Fig. 2: CAD interfaces for custom abutment modeling in (from left to right): (a) ExoCAD, (b) SolidWorks, and (c) Rhinoceros with Grasshopper.

Discussions:
Regarding the parameter management criterion (C1), notable differences were observed. ExoCAD enables patient-specific data input through predefined templates [7], supporting structured documentation in complex cases [7], consistent with Ahmed's emphasis on intuitive design for clinical adoption [1]. While effective within clinical workflows, ExoCAD's adaptability was limited when broader design control was needed. SolidWorks provides detailed parametric control [9], following solid modeling principles [10], but lacks built-in validation for dental anatomical structures [6]. Rhinoceros, with Grasshopper, enables personalized designs through visual scripting [8, 9], but demands advanced computational skills and lacks dental-specific guidance [4]. While SolidWorks and Rhinoceros allow manipulation of jaw scans [9], ExoCAD's structured data entry is advantageous in complex cases such as peri-implantitis, where clinical conditions require documentation [7]. Rhinoceros can integrate case-specific data using the functionality of Panels, whereas SolidWorks relies on external PDM or PLM systems [6]. Both SolidWorks and Rhinoceros require manual input of implant system dimensions, which can be streamlined via external Excel datasets—supported by design tables in SolidWorks and plugins like Read Excel or LunchBox in Grasshopper [8, 10]. Modification of abutment geometry (C2) also varied across approaches. ExoCAD allows basic shape adjustments without segment-level control [7]. SolidWorks enables dimension-driven editing of transgingival and prosthetic segments [9], though requiring more setup effort [6]. Rhinoceros offers the greatest geometric freedom, allowing direct

manipulation of implant connection, transgingival, and prosthesis connection segments via parametric controls [9]. Differences between the approaches were also evident concerning the model preparation for manufacturing (C3). ExoCAD supports direct STL export and CAM integration [3, 8]. Built-in restrictions, including real-time checks on minimal thickness and predefined manufacturing parameters, support readiness for production without extensive manual intervention. In contrast, SolidWorks and Rhinoceros required additional validation steps. Rhinoceros demands manual surface checks [3], while SolidWorks offers partial structural verification through FEA simulation [9]. Regarding workflow design and required expertise (C4), the approaches followed distinct patterns. ExoCAD provides a linear workflow that eases routine clinical use but limits design adaptability [7]. SolidWorks and Rhinoceros support non-linear, iterative workflows suitable for advanced modeling, though they require higher technical proficiency, particularly visual scripting skills for Rhinoceros [9]. These attributes position SolidWorks and Rhinoceros for academic and innovation-driven applications, while ExoCAD remains aligned with standardized clinical workflows. Table 2 summarizes the comparative findings.

Criteria	Dental approach	Engineering approach	NURBS-based modeling
C1) Parameter management			
C1.1	Intuitive interface tailored for dental applications	Complex, requires knowledge of surface modeling	Complex requires visual programming skills and surface modelling
C1.2	Optimized for specific dental workflows, integrates jaw scans, antagonist recognition	General engineering workflows, manual adaptation required for dental use	Adaptable but requires additional setup for dental-specific workflows
C2) Abutment geometry modifications			
C2.1	Cannot be modified; it can only be selected	Customizable via table modification	Customizable via number slider modification
C2.2	Limited adjustments via control points	Customizable via table modification	Customizable via graphs and number slider modification
C2.3	Automatic with predefined templates	Customizable via table modification	Customizable via number slider modification
C3) Model preparation for manufacturing			
C3.1	Automatically prepared for dental manufacturing technologies	Manual adjustments required	Manual adjustments required
C3.2	Compatible with dental equipment but not fully production-optimized	Needs adaptation for dental equipment	Compatible, but manual steps needed
C4) Workflow design and user expertise			
C4.1	Minimal expertise needed	Requires knowledge in dental design limitations	Requires knowledge in dental design limitations
C4.2	Minimal CAD expertise needed; user-friendly for dental technicians	Advanced CAD skills required	Basic CAD plus visual programming skills needed
C4.3	Linear, one-directional workflows streamline dental tasks but limit adaptability	Supports iterative workflows, ideal for advanced design and prototyping tasks	Iterative workflow with customizable processes

Tab. 2: Comparison between 3 different CAD approaches.

Focusing on ExoCAD, SolidWorks, and Rhinoceros in dental applications may limit the generalizability of findings, as tool performance and relevance vary depending on the specific dental application and user requirements. It is suggested that future work, following the example of Kosec's comparison of dental-specific tools [6], should also include comparisons within engineering-based and NURBS-based approaches to identify which tools best support dental applications and understand the reasons for their performance. The qualitative approach provides user insights but lacks the quantitative data necessary for broader validation. Quantitative studies on modeling speed, error rates, and user satisfaction would further support evidence-based CAD development [3]. A hybrid approach combining

ExoCAD's dental-specific functionalities with Rhinoceros' modeling adaptability could better address complex prosthetic cases, especially if clinical semantics are incorporated [9]. Although Rhinoceros supports adaptable workflows, its clinical usability remains limited without predefined dental functionalities. Enhancing user training and automating workflows, through platforms such as Grasshopper or ExoCAD, could lower entry barriers and facilitate adoption across expertise levels [7]. Finally, integrating real-time collaboration tools, as available in Rhinoceros, may strengthen interdisciplinary workflows and reduce iteration cycles [8].

Conclusions:

Selecting a CAD approach for custom abutment design involves balancing dental-specific functionalities and geometric control. ExoCAD supports standardized workflows but limits design flexibility. SolidWorks and Rhinoceros offer greater control and multi-component modeling, yet require more expertise and manual integration of clinical data. While powerful, their complexity may reduce usability in practice. These findings underline the importance of aligning tool capabilities with clinical needs and suggest future exploration of hybrid approaches combining advanced modeling with dental functionalities.

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