Title:
Towards Mass Personalization in Dentistry: Analysis of Dental CAD Tools

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Introduction:
Mass personalization (MP) represents a revolutionary production paradigm that transcends traditional mass production by systematically personalizing products on a large scale to meet individual customer preferences and needs [8]. This approach harnesses advanced design methodologies, digital technology, and user-centric processes to deliver tailored products efficiently. Design for mass personalization (DfMP) necessitates a departure from conventional product development methodologies to fulfill MP requirements. Authors [5], [7], [10] address enabling product variability and customer involvement as key MP characteristics; however, challenges persist in translating customer needs into design parameters due to a lack of generalized MP design methodology [8], CAD tools that do not fully support MP aspects [5] and customers' lack of technical expertise [7]. While specialized CAD tools and data-driven design have enabled customer involvement and product variability, the development of a general methodology for mass personalization design is still limited to specific cases. Berry et al. [1] proposed an open platform design methodology for MP, comprising common, customized, and personalized modules [3]. However, this approach may limit customization [10] and accessibility for non-technical users [7]. Ozdemir et al. [7] introduced a seed design methodology focusing on adaptable parametric geometry but faced challenges in interaction between functional and physical domains. Despite demonstrations of personalized design [11], current research fails to specify the implementation of MP in CAD tools or their application to large-scale production products. One example is the dental industry, which is characterized by its focus on tailoring dental prosthetics such as custom abutments, crowns, bridges, and dentures to the unique oral anatomy and functional requirements of each patient. This personalized approach not only enhances patient satisfaction but also ensures superior fit, comfort, and functionality, leading to improved treatment outcomes. Central to the realization of personalisation in dentistry are specialized dental CAD tools. These sophisticated software applications utilize parametric design, digital scanning, and 3D printing technologies to design and fabricate custom dental prosthetics. However, literature on the design processes within these tools is scarce, underscoring the need for further research in this area. Closing this knowledge gap will facilitate the integration of MP principles into CAD tools and enhance their effectiveness in meeting the diverse needs of consumers across industries.

Objective and methodology
The main objective of this study is to explore how dental CAD tools adhere to MP principles and offer valuable insights for enhancing and developing CAD tools in the dentistry field. Our study compares four dental CAD tools, uncovering insights into their capabilities and limitations concerning MP. Criteria for this comparison are extracted from a literature review, encompassing current design methodologies, procedures, and approaches for MP. By extracting relevant criteria, we aim to establish a framework for

evaluating and comprehending the effectiveness of these CAD tools in the context of MP. The chosen CAD tools – ExoCAD Rijeka 3.1 [12] and 3shape Dental System 2023 [13], leaders in the dental industry, Straumann Nova 2023 [14], a recently developed tool from a prominent implant manufacturer - Straumann, and UpCAD [15], an emerging CAD tool, were selected to represent a comprehensive range of technologies. The comparison focuses on the design of an individual dental implant abutment, which acts as a connector between the implant in the jawbone and the visible part of the restoration (crown, bridge, or denture). The abutment design consists of three main segments: the implant connection segment, trans gingival segment, and prosthesis connection segment (refer to (Fig. 1). The implant connection segment is shaped to fit the geometry of the placed implant and ensures stability and a secure seal between the implant and the prosthetic restoration, commonly referred to as "passive fit." The trans gingival segment conforms to the oral tissue around the implant, mirroring the natural emergence profile of a tooth. The prosthesis connection segment is tailored to the shape, size, and type of prosthetic restoration that attaches to it using dental cement. While both segments adhere to specific guidelines for dental abutments, they are uniquely designed for each patient and must consider individual design constraints.

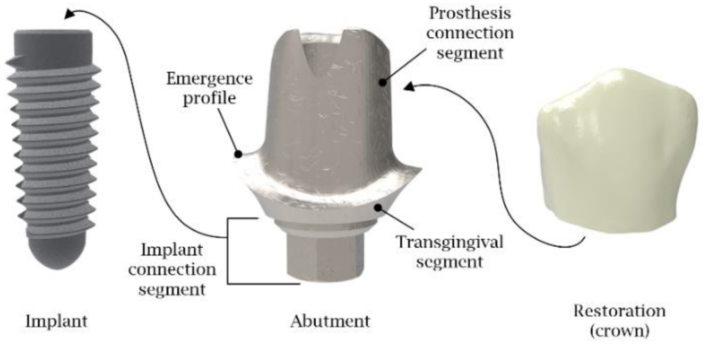

Fig. 1: Abutment segments and connecting parts (implant and crown).

Through a literature review on mass personalization (MP) in the design phase, several key aspects have emerged, notably in seed (initial) design definition and manipulation. The definition of a seed design has a pivotal role in initiating the design process by allowing users to build upon existing frameworks tailored to specific needs [2]. The literature emphasizes the significance of generating a product using a pre-designed functional module of a product (open architecture product design approach and seed design approach), setting the platform for customization and personalization, and streamlining the design workflow. Additionally, the capacity to automatically generate seed designs using input data and constraints is highlighted as essential for enhancing efficiency and reducing dependency on manual intervention [7]. Furthermore, the literature underscores the importance of supporting parametric manipulation and customization of seed designs [6], empowering users to fine-tune product specifications to align with individual preferences and requirements. Effective management of design constraints is crucial, dictating the extent of user-modifiable parameters and facilitating iterative design processes [9]. Visual representation of design constraints provides real-time feedback, guiding users in maintaining design integrity and compliance [11]. The systematic guidance through the design process ensures consistency and efficiency, particularly in complex customization scenarios, fostering continuous improvement and refinement [4]. Moreover, the literature emphasizes the tool's capability to manage design complexity, including handling intricate geometries and accommodating functional features within personalized designs [6]. Advanced geometry manipulation techniques are highlighted for enabling precise control and optimization of personalised designs, ensuring they meet exacting standards of quality and functionality.

By synthesizing insights from existing research studies related to MP, a list of design criteria for comparing CAD tools has been compiled (Tab. 1).

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Criteria	Description
C1) Seed design definition and manipulation [2,6,7]	ability to define a dynamic product template using different user-input data
C1.1	ability to select the predesigned functional domain of the product
C1.2	ability to generate seed design automatically using input data and constraints
C1.3	support for parametric manipulation and customization of seed design
C2) Design constraints management [9,11]	the ability of CAD tool to define and manage constraints within the problem space, guiding the exploration of the design space and identifying feasible solutions within the solution space
C2.1	extent of user-modifiable constraints and parameters
C2.2	ability to change design constraints during the design procedure
C2.3	ability to visually represent if the design exceeds design constraints
C2.4	ability to add custom parameters
C3) Procedural design capabilities [4]	capability to guide the user through the design process following predefined procedures or rules
C3.1	the ability of iterative design
C4) Design complexity handling [6]	ability to handle and accommodate intricate geometries or functional features in personalized designs
C4.1	advanced geometry manipulation techniques
C4.2	ability to use free-form options
C4.3	ability to add additional functional features (custom-made features)

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

Results and discussion

A comparison table was compiled to assess the performance of four CAD tools based on predefined criteria. This qualitative evaluation determined each tool's support for MP design criteria.

	ExoCAD Rijeka 3.1	**3shape 2023**	**Straumann Nova 2023**	**UpCAD 2023**
	C1) Seed design definition and manipulation			
C1.1	implant connection segment is predefined using a database of implants			
C1.2	seed design is generated using input data such as oral scans, predefined design parameters, autodetected emergence profile, shape of the restoration, tooth position, implant placement, etc.			seed design has a generic shape; it is not shaped according to input data
C1.3	each segment of the design is manipulated using parameters			
	C2) Design constraints management			
C2.1	an extensive list of parametric design constraints		a basic list of parametric design constraints	
C2.2	restricted ability to change constraints during the design process		does not have the ability to change constraints during the design process	
C2.3	visual representation when the design exceeds the defined constraints		does not support visual representation when design exceeds defined constraints	
C2.4	has the option to add custom parametric constraints	no option to add custom parametric constraints		
	C3) Procedural design capabilities			
C3.1	each segment of an abutment is designed procedurally			
C3.2	has the ability for the incremental iterative design procedure	has the ability for iterative design procedure		
	C4) Design complexity handling			
C4.1	manipulation using predefined planes, curves, and control points with an option for adding additional control points		manipulation using predefined planes, curves, and control points	

C4.2	available free-form options (sculpt tools)	
C4.3	have the option to add third-party and user-designed features (geometry import)	does not have an option to add additional third-party or user-made features

Tab. 2: Comparison between 4 different CAD tools

The design process in all four dental CAD tools begins with defining the implant connection segment, which is a platform for the subsequent abutment design. In the context of seed design, this segment lays the foundation for the trans gingival and prosthesis connection segment. Users select the implant connection segment via the tool's interface, utilizing predefined geometries established by the manufacturer, which are unalterable by users. These geometries come with predetermined constraints, including minimum height and width of the trans gingival segment, minimum hole diameter for screw fixation, and minimum dimensions of the prosthesis connection segment. This approach parallels the open platform design method, where the manufacturer defines and constrains the common module while users dictate customizable and personalized modules. ExoCAD, 3shape, and Nova go further by enabling the generation of initial abutment shapes based on loaded oral cavity scans, implant geometry, and crown shape. This process is guided by predefined parameters specific to the selected abutment and prosthetic crown material. ExoCAD stands out with the option to add custom parametric constraints, although requiring advanced user knowledge for configuration file customization. This feature significantly streamlines seed design generation, automating the process for mass personalization (MP). Conversely, UpCAD lacks automatic optimization or adaptation of abutment design, necessitating user-driven parametric design. Nevertheless, all tools support parametric design for optimized abutment shapes, expediting the design process. During abutment design, constraints defined at the beginning are adjusted only within predetermined ranges. Tools like ExoCAD and 3shape ensure continuous display and enforcement of minimum thickness requirements, enabling users to visualize designs while preventing violations of set constraints in the final product. Nova and UpCAD offer similar features but lack the ability to visualize designs below minimum thickness requirements. These restrictions are crucial for maintaining the integrity of the solution space, preventing the creation of products beyond permissible limits, which means neither the algorithm nor the user can produce topologically invalid geometry during seed design generation or manual manipulation. All four tools adopt a structured, iterative design approach, supporting workflow efficiency and design process uniformity across various projects. This iterative process facilitates continuous improvement and refinement, integrating patient feedback to meet evolving requirements and enhance patient satisfaction. ExoCAD's incremental, iterative design feature allows the direct incorporation of modifications within specific design steps, autonomously adjusting the remainder of the design to align with the modified geometry. To enhance customisation and individualization, all tools provide advanced design manipulation options using planes, curves, and control points. ExoCAD and 3shape offer adding additional control points, enabling the creation of intricate geometries and utilization of sculpting tools. Furthermore, both tools allow the import of custom-made functional geometry, enhancing adaptability to diverse therapy needs and individual patient requirements. This feature facilitates the addition of technological geometries for faster and more efficient production, such as support or rigidity structures for additive manufacturing.

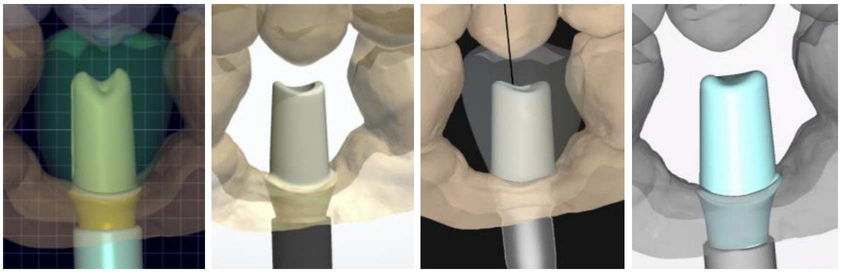

Fig. 2: Designed abutment in (from left to right): ExoCAD; 3shape; Straumann Nova; UpCAD.

Conclusions:

In conclusion, the evaluation of four dental CAD tools highlights the ability to generate seed design using input data (intraoral scans) and structured design approach, alongside their support for parametric design and iterative refinements. Notably, ExoCAD and 3shape stand out for their comprehensive feature sets, including advanced design manipulation options and support for importing custom-made functional geometry, which enhance adaptability to diverse therapy needs and individual patient requirements. However, despite their strengths, areas for improvement exist, particularly in the interpretation of design requirements and the automation of processes. Future advancements, such as generative design and machine learning algorithms, hold promise in mitigating user expertise dependence and automating aspects like abutment shape optimization based on patient data and production requirements. Further research is warranted to quantify the impact of these advancements on design and production efficiency, as well as to assess their broader applicability across a wider range of data and case studies.

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