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# Robust tooth surface reconstruction by iterative deformation

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ABSTRACT

Digital design technologies have been applied extensively in dental medicine, especially in the field of dental restoration. The all-ceramic crown is an important restoration type of dental CAD systems. This paper presents a robust tooth surface reconstruction algorithm for all-ceramic crown design. The algorithm involves three necessary steps: standard tooth initial positioning and division; salient feature point extraction using Morse theory; and standard tooth deformation using iterative Laplacian Surface Editing and mesh stitching. This algorithm can retain the morphological features of the tooth surface well. It is robust and suitable for almost all types of teeth, including incisor, canine, premolar, and molar. Moreover, it allows dental technicians to use their own preferred library teeth for reconstruction. The algorithm has been successfully integrated in our Dental CAD system, more than 1000 clinical cases have been tested to demonstrate the robustness and effectiveness of the proposed algorithm.


## 1. Introduction

In recent years, the CAD technique used in the dental CAD/CAM system has been equipped in many dental groups and laboratories [1–5]. Compared to the traditional manual restoration, the CAD technique can significantly reduce the labor intensity of technicians, enhance the quality of restoration, and meet individual needs [6].

The all-ceramic crown has become increasingly popular in recent years. Compared to the conventional porcelain-fused-to-metal (PFM) crown, the all-ceramic crown emphasizes the cosmetic result [7]. The PFM crown can hardly meet requirements for the incisor restoration, but the all-ceramic crown can achieve satisfactory results [8]. In addition, the all-ceramic crown is becoming increasingly popular because of its excellent biocompatibility. To deliver an almost ideal crown, several processes need to be done, such as scanning the plaster model, reconstructing the crown's surface, modifying the designed crown in a virtual or simulative stomatognathic environment, and strength analysis of the dental crown. These essential processes enable the crown to follow the masticatory function, the envelope of movement permitted by the occlusion, temporo mandibular joint and neuromuscular systems.

Reconstruction of the crown's surface includes several cascaded operations, as shown in Fig. 1. Before the design process, the preparation has marked a specific identify to help selecting the proper standard tooth in the design. Fig. 1(a) is the scanned preparation model with its neighboring and antagonist teeth; the first step is to extract the margin line of the preparation (Fig. 1(b)). The second step is to cut the preparation into two parts, the unprepared part and the prepared surface (Fig. 1(c)); the third step is to calculate the insertion path from which we can see the largest visible area of the upper part (Fig. 1(d)); the fourth step is to offset the upper part by a given distance (Fig. 1(e)) to simulate the use of a die spacer; the fifth step is to select a corresponding standard tooth which has been numbered in the standard tooth library, and to position the standard tooth (Fig. 1(f)); the sixth step is to reconstruct the outer surface of the crown (Fig. 1(g)); the seventh step is to modify the outer surface of the crown to achieve a proper occlusion (Fig. 1(h)); the eighth step is to merge the inner surface and outer surface together to finish the whole design (Fig. 1(i)). In this paper, we only focus on the process of reconstructing the crown's outer surface (the sixth step).

In the all-ceramic crown CAD design system, recovery of the whole tooth crown is difficult using only information from the tooth preparation, as shown in Fig. 2. A common method is to use the information of a standard tooth. By applying the position and scale to a standard tooth, an initial shape of a tooth crown can be obtained [9,10]. The tooth crown is then deformed to fit closely to the prepared tooth's margin line (Fig. 2). However, following two main problems can be encountered in the existing methods:

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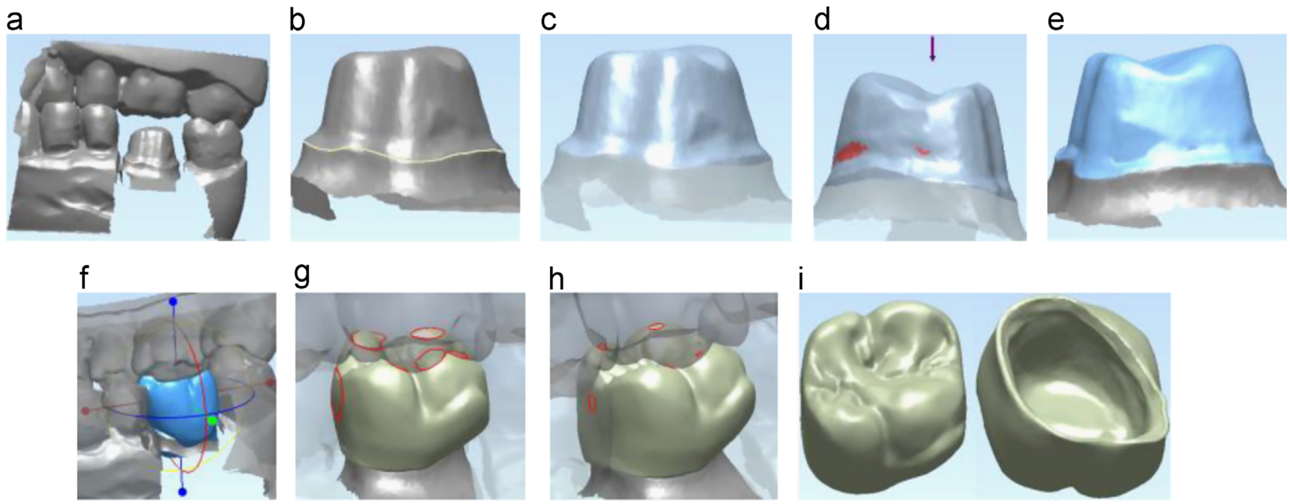


**Fig. 1.** The cascaded operations of the whole design.

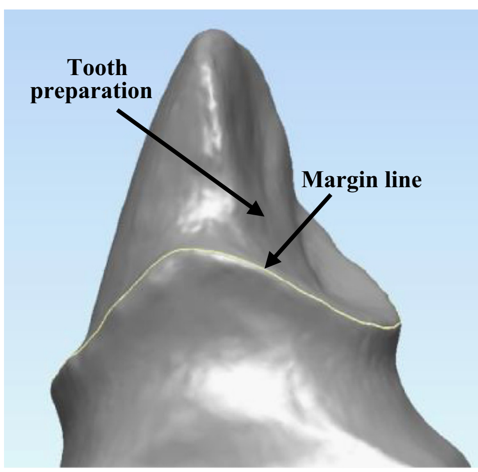


**Fig. 2.** Tooth preparation and margin line.

(1) Adjustment of the occlusal surface is difficult for these methods because of the presence of numerous cusps, fossas, ridges, and sulcus. Retaining these morphological features is a challenging task.
(2) Most existing methods [11,17–21] are only suitable for molars, they have certain limitations in clinical applications.

To solve the two aforementioned problems, this paper presents a robust tooth surface reconstruction algorithm. The algorithm involves three steps. First, a standard tooth is initially positioned and divided into three zones. Second, salient feature points (SFPs) are extracted from the standard tooth using Morse theory. Third, the standard tooth deforms iteratively using these SFPs and meshes are stitched. By extracting SFPs, the algorithm can retain the morphological features of the occlusal surface well. The division of the standard tooth into zones and the iterative deformation technique make the algorithm suitable for almost all repair types in clinical settings.

## 2. Related work

Many researchers have developed CAD/CAM systems and presented various methods, such as Duret system, Minnesota system, and GN-I system, for the teeth surface design. The Duret system was initially developed in France. It is highly inconvenient and can only implement simple tooth surface restoration [12]. The Minnesota system uses an affine transformation of a 3D tooth model for a scanned tooth. However, the system cannot cover all kinds of restorations, and it is mainly used for crown production [13]. The GN-I system designs the occlusal surface of a tooth by the contact simulation. However, this system has difficulty in establishing customized articulation relations because of a lack of different forms of tooth surface design [14].

Many methods can be considered to design the tooth surface. The key to this process is the design of a fine deformation method to reconstruct the tooth surface. Many deformation methods are used to design the tooth surface. Zeid [15] used the free form deformation technique through a set of control points to design the tooth crown. This process is complicated because the tooth surface is complex. Adolph et al. [16] and Gürke [13] used geometrically deformable models to recover the tooth surface. This method first adopts a low-resolution mesh of the model tooth by the energy-driven deformation, and the low-resolution mesh is gradually refined. This method can achieve attractive results in many cases. However, it fails to cover the full range of possible clinical situations. Steinbreche et al. [17] and Zhang et al. [18] used the differential deformation technique to reconstruct the missing teeth surface. This method is robust, however, it does not consider the morphological features on a standard tooth, resulting in the loss of numerous details. In addition, this method is only suitable for molars. Zheng et al. [19] presented a morphing approach for the tooth occlusal surface reconstruction. By establishing one-to-one special mapping relation between the standard tooth and the tooth preparation, a mapping function called radial basis function is used to achieve the tooth surface deformation. This method is only suitable for molars. Moreover, the shape of the tooth preparation is remarkably different and strange, and the tooth preparation often exhibits no distinguished features. Thus, Zheng's method may not be clinically suitable. Blanz et al. [11] and Mehl et al. [20,21] used a biogenetic tooth model using many single teeth to reconstruct the crown. During construction, a certain number of points (e.g. cusp tips and contact points) are also required. This method requires complex theories and much computation, and these points are obtained almost by hand. To date, this method has only been used for molars and premolars.

The aforementioned methods use the tooth library to reconstruct the tooth surface. The tooth library is vital for tooth surface reconstruction. Cheng et al. [22] established a standard tooth library as the basis for a dental CAD/CAM system. Other studies have also been conducted for the dental reconstruction, such as