Automatic evaluation of Crown Preparation using Image Processing Technique: A substitute to Faculty Scoring in Dental Education

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Abstract:

Introduction: In this study, a new and innovative experimental method including software and its prerequisite instruments is presented to use image processing techniques for crown preparation analysis

Method and Materials: A platform was designed and constructed to acquire images from artificial teeth in different angels and directions and to process and analyze them by proposed methods to evaluate the quality and quantity of crown preparation. For each tooth, two series of images were taken from artificial teeth before and after preparation and image series were registered by two semi-automated and automated methods to transform them into one coordinate system. Region of interest was segmented with user interaction and tooth region was segmented with sub-steps including transformation to HSV color space, edge detection, morphology operations and contour extraction. Finally, amount and angle of crown preparation were computed and then compared with standard measures to evaluate the qualification of crown preparation. The proposed method was applied on a local dataset collected from Isfahan University of Medical Sciences.

Results: Difference between the angle of crown preparation computed by the proposed method and experts has average absolute error of 7.17. The correlation between segmented regions by proposed method and experts are also evaluated with intersection over union (IOU) criterion. The best and worst performances achieved in cases with IOUs 0.76 and 0.94, respectively. Finally, the segmentation results of the proposed method have average IOU of 0.89 in all images.

Conclusion: This method can be used as assessment tool for students work in pre-clinic of tooth preparation to compare their crown preparation with standard parameters.

Key words: dental education, assessment, grading, preclinical simulation, Prosthodontic Tooth Preparation, Computer-Assisted Image Processing

1. Introduction

Teeth do not possess the regenerative ability found in most other tissues. Therefore, once enamel or dentin is lost, restorative materials must be used to reestablish form and function [1]. Crown preparation is essential before restoration stage, and the preparations must be based on fundamental principles to establish basic criteria to predict the success of care in future [2].

In dentistry, crown is one of the most widely used fixed restorations. The restoration process consists three groups; full metal, metal-ceramic and full ceramic crowns. A full metal crown is a full coverage metal restoration with low level of esthetic options. A metal-ceramic crown is a full coverage cast metal crown covered with a layer of fused porcelain to reproduce the aspect of natural tooth in both shape and color [3]. All-ceramic crowns are the most pleasing esthetic restorations which mimic original tooth color better than other restorative options [4].

Such a restoration requires specific tooth reduction to provide space for metal and/or ceramic layers of crown along with tooth structure preservation. Crown preparation should with considerable tooth reduction, would leads to appropriate shape and thickness and guarantee natural tooth duplication and structural durability.

Insufficient tooth reduction may lead to a compromised appearance of restoration or over-contoured restorations may appear at expense of proper axial contour which lead to periodontal disease. Sufficient tooth removal is needed to provide a distinct fishing line to host the material [5]. The recommended reduction in literature for different material and for different views of tooth range from 0.7 in full metal to 2 mm in all-ceramic crowns [6].

Appropriate degree of taper for crown preparation is also another important aspect in crown preparation. Too small taper may lead to unwanted undercuts (causing unfitted restoration and possibility of tooth decay or tooth loss). Too large taper leads to a frequent decemntation of the crown. Textbooks in fixed prosthodontics often recommend a convergence angle of approximately 5° (4–6°) as the ideal and a range of 4–14° as acceptable [7-8]. However, these guidelines are difficult to follow clinically, and divergence from parallel might have to be as much as 12° to be observed clinically as diverging surfaces. Mack observed that a minimal taper of 12° was necessary to ensure the absence of undercuts [9]. Goodacre et al. proposed that the total convergence angle (CA) should range between 10° and 20° [10]. Other investigators have recommended 10° and 16° CA based on laboratory studies—[8]. The recommended convergence between opposing walls is 6 degrees, which is shown to optimize retention for the crown. One of the most important sections in dental education is fix prostho pre-clinic. Achieving the proper skills in this section is vital for becoming the next dentists. Progress for students in this field depends on hard practice and one of the effective ways to provide efficient practice for students is developing a self-examination system.

There are several methods to evaluate the quality and quantity of preparation. The most accurate method to evaluate crown preparation is making a proper impression; producing stone die and carry out two dimensional scan of it followed by measuring the preparation thickness and convergence angel [11]. This method is not practical in pre-clinic lab for several students due to time restrictions and need to additional steps. The current feasible method to evaluate the preparation is undercut detection by an expert. There is no doubt that subjective evaluation suffers from inter-subjective differences and is a time consuming process to be used.

The proposed method presents a device to calculate immediate and accurate measure of tooth preparation for dentistry students. A portable simple device with reasonable price and reliable measurement could play a great role in skills improvement of students and help them to achieve proper levels of skills during their academic education.

In this study, we are going to introduce and evaluate the efficacy of a new and innovative experimental method including a software and its prerequisite instruments to use image processing techniques in order to remove the role of faculty in assessment of students work in pre-clinic of tooth preparation.

2. Methods and materials:

This study is based on the result of a technology-based research approved by the research council in Isfahan University of Medical and the invention is approved by the intellectual property center of state organization for registration of deeds and properties, Iran (No 98352).

The block diagram of the whole process is shown in figure 1.

In this research, a software is designed and implemented in Qt platform with C programming language and OpenCV image processing libraries. Qt is a technology strategy that lets programmers quickly and cost-effectively design, develop, deploy, and maintain software while delivering a seamless user experience across all devices. The software has graphical user interface (GUI) in which tooth images can be easily loaded and crown preparation parameters are computed and compared with parameters achieved from gold standard images. The source code of this software will be publicly available after the publication of the paper.

In other softwares such as E4D, prepared crown by students is scanned with 3D methods and then compared with 3D scans of the prepared crown by individual faculty members as gold standard cases. Here, parameters of crown preparation are computed automatically with image processing techniques. Extracted parameters can be compared with standard and pre-defined parameters to evaluate crown preparation qualitatively and quantitatively. This is the main difference between the proposed software in this research and other softwares.

3. Image Registration

In first step, for each tooth, two sets of images are acquired from artificial teeth before and after crown preparation. Photographs were taken using a box prepared for this objective.

Camera positions are set to 0 and 90 degrees with respect to horizontal surface in adjustable holders proposed to keep different cellphones (referred as Facial and Occlusal images, respectively). This box is in black color with a light source in it, and an especial place to settle the plastic arc and a graded movable platform to enable students to resettle the arc in its exact place for taking the post images. The box has two holes, above and in proximal side, enabling the users to take two images from facial and occlusal sides.

The images before and after crown preparation are called FirstImg and SecondImg, respectively in this paper (figure. 1). Four images are then stacked to calculate crown preparation parameters. The first step in parameter calculation is image registration which is the process of transforming different sets of images into one coordinate system. Here, two procedures for image registration are examined.

The first method is a semi-automated method with user interaction. In this method, 4 points are selected by user from FirstImg followed by selecting 4 corresponding points from SecondImg. Then, a transform is found by homography functions to map first 4 points to second ones. Presence of 8 anonymous parameters in homography function justifies the need for 4 points.

The second method is an automated method in which two sets of key points from FirstImg and SecondImg are detected by surf detector [12] and then described by descriptors. In the next step, Flan adaptor finds the best match between points among two sets. Finally, a transform is computed to provide registration for matched points.

4. Extraction of Region of Interest (ROI)

In this specific application, the region of interest is a limited region located around the prepared tooth. The calculations showing quality of preparation become very difficult if the region would not be limited around the tooth of interest. Therefore, ROI is selected by user interaction by mouse drag, resulted in rectangular region for ROI. Figure 3 shows a sample acclusal image before and after ROI selection.

5. Tooth segmentation

The main goal of this research is to localize the tooth boundary and compute crown preparation parameters. For this purpose, the following steps are applied sequentially.

5.1. Transform to HSV color space

To discriminate background region from ROI, color differences are utilized. For this purpose, HSV color domain provides better representation in comparison with RGB color thresholding [13]. In the first step, reference ranges of H, S and V components are considered for tooth regions empirically. Then, HSV components of each pixel are compared with reference ranges to be assigned to tooth or background. Figure 4 demonstrates a binary image after thresholding in HSV color domain.

5.2. Edge detection

To compute the perimeter and area of tooth before and after tooth preparation, tooth edges should be segmented which leads to tooth contours. Here, canny edge detector is used with two thresholds T1 and T2 [14]. If pixel gradient is greater than T2 this pixel is marked as edge, and for the case of being between T1 and T2, it is also considered as edge if the pixel is placed close to a current edge. Figure 5 shows the result of canny edge detection applied on selected ROI.

5.3. Morphologic operations

As it is clear from figure 5, extra edge pixels in background are segmented by edge detection method. This problem affects the next steps of processing. To address this issue, morphology operations are used [15]. The main purpose to use such operations is to achieve convex and continuous contours. "Erosion" morphology operation is applied to images before edge detection phase. This operation removes small white regions and creates continuous dark regions in background. Figure 6 depicts segmented edges of a ROI image with and without morphology operation.

For images taken from occlusal view,, "dilation" operation is applied to find internal counter. This operation connects white regions and a sample image is demonstrated in Figure 7 to show the edges before and after dilation operation.

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5.4. Contour extraction

5.4.1. Contour extraction from Occlusal images

For Occlusal images, interior and exterior contours of teeth are extracted. To find exterior contour, different window sizes are considered for structure element which leads to extract different contours. The concaveness of extracted contours is compared with a threshold and a contour with the concaveness more than a threshold is selected. In case that there is no contour with this condition, the contour with the lowest concaveness is selected. To find interior contour, edges are detected by canny algorithm followed by dilation operation to connect discrete edges. Second maximum is selected among all extracted contours. If the concaveness of the selected contour is less than a threshold, it is selected as final interior contour, otherwise contour with the minimum concaveness is selected. A sample of interior and exterior contours by the proposed method and expert is depicted in figure 8.

5.4.2. Contour extraction from Facial images

For Facial images, perimeter of teeth should be considered. Therefore, the biggest extracted contour is selected with the similar method discussed in section 3.4.1.

5.5. Crown preparation computation from extracted contours

The main objective of tooth images processing and contour extraction is to determine irregular and regular parts of tooth preparation. After contour segmentation, goodness of crown preparation can be quantitatively evaluated. For this purpose, all corresponding points located in interior and exterior contours are considered counterclockwise which is shown in Figure 10.

It is expected that two interior and exterior contours have smooth changes and be in similar distance. Namely, by assigning a threshold, contour differences more than a threshold is considered as error (figure 11, red colors).

5.6. Crown preparation angle

Crown preparation angle is another parameter which can be extracted from Facial images. Two lines in sides of teeth region (after preparation) are considered to compute crown preparation angle. The procedure for this task is that at first the center of contours is determined and then the contour is divided into two right and left sections. Two angles are then calculated for each section, amount of which, along with its symmetry in two sides are considered for correct teeth preparation (figure 12).

6. Experimental Results

In this research, HSV color space is used for tooth preparation. To find color range of tooth, in each HSV color component, either upper bound or lower bound is fixed and then another bound is changed to reach the maximum accuracy for tooth segmentation. For H component, upper bound is fixed with 255 and lower bound is selected among quantities 5, 10, 15, 20. Note that in this experiment, all tooth images are segmented correctly only in lower bounds [5, 10, 15, 20]. Table 1. reports accuracies of tooth segmentation in each tooth for different lower bounds of H. It is clear that lower bound 10 (h_min=10) achieves the best accuracy 0.89. Therefore, bound [10 255] is selected as final range for component H. With a similar procedure, bounds [0 93] and [208 255] are selected for components S and V, respectively. For components H and V, upper bound 255 are fixed while for component S, lower bound 0 is fixed.

Erosion as a morphology operation is applied to images before edge detection phase (to remove small white regions and to create continuous dark regions in background). The most important parameter in this operation is the window size referred as *kerode or stride*. The bigger quantity for window size, the more white area around tooth edge is removed which leads to elimination of tooth edge. For window size, the upper bound is fixed to 40 and the lower bound is selected among set [5, 10, 15, 20, 25, 30, 35]. Accuracies for different window sizes are reported in Table 2. The window size 5 achieves the best average accuracy of 0.89.

The window size for dilation is also explored for occlusal and facial images. . For dilation, the upper and lower bounds are considered as 12 and 5, respectively with quantities 7 and 10 between these bounds. Note that for window sizes 12 and less, all contours can be segmented correctly. This is the reason of selecting 12 as upper bound. As it is clear from reported accuracies for different window sizes in Table 3, window size 7 is the best parameter for dilation.

The last parameter is threshold for canny edge detector. Canny uses two thresholds T_min and T_max for edge detection. Here, T_min is considered as 0 and T_max is selected from a range with a similar way for erosion and dilation parameters. Note that based on this experiments, canny can correctly segment the edge of all images only in interval [20-25] for T_max. Therfore, T_max is evaluated for quantities 20, 23 and 25 in which the highest accuracy 0.88 was observed in T_max=25 (Table 4).

To show the effectiveness of the proposed method, the results are compared with ground truth labels by experts. Segmented contours by proposed method and by experts in sample pairs of Facial images are shown in figure 13 with cyan and green colors, respectively.

Segmentation results for sample pairs of occlusal images are also depicted in figure 14.

The first parameter for evaluation is the angle of crown preparation computed by the proposed method and experts. Table 5 reports the angle computed from ground truth and the proposed method as well as difference (Error) and absolute difference (Absolute Error) between these angles for 12 images with numbers 10-21. The best correlation between the crown preparation angle in gold standard and the proposed method is achieved in image 10 with absolute error of 2.5 degree while image number 21 is the worst case with absolute error of 10.85. The average absolute error for all images is 7.17.

The correlation between segmented regions by proposed method and experts are also evaluated with intersection over union (IOU) criterion. Table 6 reports the IOU for all images with numbers 1-21. The best and worst performances achieved in images 10 and 21 with IOUs 0.76 and 0.94, respectively. The segmentation results of the proposed method have average IOU of 0.89 in all images.

The internal and external contour segmentation are also done by the proposed segmentation method. The IOU between internal and external contours segmented by the proposed method and experts are reported in Table 7. It is concluded that external contour with the IUO of 0.93 is segmented more accurately in comparison with internal contour with 0.88.

7. Discussion

Accurate and fair assessment of student work are usually considered as the most critical phase of education. In preclinical dental education, students need to receive consistent and accurate feedback from faculty in order to achieve a higher level of performance before advancing to the clinics [16]. However, according to attributors leading to disagreement about student work including grading scale, rater calibration, and subjective influences, providing consistent feedback by faculty is very difficult [17].

Valid and objective criteria would help resolve the grading crisis in dental education which partly can be achieved by removing the human element from evaluation and develop objective evaluation methods [18-19].

Computer-aided system are using in different dental schools around the word that offer many feedback options and the ability for self-assessment. The Simodont Dental Trainer (ACTA, Amsterdam, Netherlands) enables students to "develop their manual skills in a realistic virtual world, while getting feedback on their decisions and abilities. Sirona (Salzburg, Austria) describes its prepCheck as an easy-to-learn application based on objective measurement procedures with the ability to document and analyses students' results [20].

Recently, E4D Compare software program (Richardson, TX, USA) have also been introduced with the ability to evaluate the prepared teeth throughout three dimensional technique [21]. Although the described above instruments have been shown to have successful outcomes, they are based on high-tech and high-price scanner systems. Also, in these systems, the tooth prepared by students need to be compared by the tooth prepared by their supervisor faculties that poses the evaluation at risk of human judgment again. Besides, for E4D system it was shown that conventional grading by the faculty did not correlate within an acceptable range derived using this software [22].

In our study, we have introduced a novel and convenience method for evaluating the quality of tooth prepared by dental students for metal-ceramic tooth preparations. However, the innovated instrument have the potential to be planed for other crown materials also by defining the cut-off-points . This invention might improve the objective, and repeatable judgment of students' work in pre-clinic. Also, application of this method is not related to high-tech methods like scanner systems and is more user-friendly. The pre and post preparation photos can be taken by cellphones of students.

In proposed method, the best results in segmentation of contours are achieved in cases with good imaging quality (appropriate light and imaging angle). However, our segmentation method is designed to be less sensitive to changes of such conditions. Furthermore, perfect segmentation is evident in specific regions of the image with appropriate range of RGB color spaces. As it is clear from figure 13, in some cases where these conditions have significant changes, the proposed method fails in correct segmentation. For example, if the color of gingiva is close to dental color, the proposed method misleads the contour path and segments smaller dental region. This scenario is also valid for both Facial and occlusal images. For internal contours, when the edge of crown preparation is not clear, the contour will be segmented incorrectly and leads to lower accuracy. Furthermore, if the side regions of the teeth are changed significantly, it is difficult to fit a single line and an error in angle computation appears.

8. Conclusion

In this research, a new package including software and its prerequisite instruments was proposed to help students in pre-clinic of tooth preparation. For this purpose, images from artificial teeth were taken in different angels and directions before and after crown preparation and then analyzed by proposed methods to evaluate the quality and quantity of crown preparation. The proposed methods for tooth image processing had image registration, region of interest segmentation, transformation to HSV color space, edge detection, morphology operations and contour extraction which led to compute amount and angle of crown preparation. Applying proposed platform to a local tooth dataset showed average absolute error of 7.17 and average IOU of 0.89 in comparison to gold standard images segmented by experts. Our method of evaluation seems totally a convenience aid for dental students to evaluate their work. However, before application of this method as part of dental education, accuracy and validity of the outcomes should be tested in comparison to faculty grading, the situation happens routinely in dental schools.

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Table 1. Accuracies for occlusal images with selection of different lower bounds for component H.

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Images No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	Ave.
h_min=5	0.92	0.94	0.91	0.87	0.94	0.93	0.9	0.91	0.92	0.75	0.77	0.8	0.88	0.9	0.86	0.83	0.88	0.87	0.81	0.89	0.93	0.87
h_min=10	**0.93**	**0.94**	**0.89**	**0.87**	**0.94**	**0.93**	**0.89**	**0.9**	**0.91**	**0.76**	**0.84**	**0.8**	**0.92**	**0.93**	**0.94**	**0.92**	**0.92**	**0.94**	**0.8**	**0.89**	**0.94**	**0.89**
h_min=15	0.93	0.93	0.88	0.86	0.93	0.92	0.86	0.89	0.89	0.77	0.8	0.8	0.88	0.89	0.92	0.88	0.93	0.93	0.79	0.89	0.91	0.88
h_min=20	0.91	0.89	0.87	0.78	0.91	0.9	0.79	0.84	0.84	0.69	0.66	0.8	0.8	0.82	0.83	0.77	0.92	0.9	0.72	0.77	0.72	0.82

Table 2. Accuracies for occlusal images with selection of different window sizes for erosion.

Images name	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	average
kerode = 5	**0.93**	**0.94**	**0.89**	**0.87**	**0.94**	**0.93**	**0.89**	**0.9**	**0.91**	**0.76**	**0.84**	**0.8**	**0.92**	**0.93**	**0.94**	**0.92**	**0.92**	**0.94**	**0.8**	**0.89**	**0.94**	**0.897**
kerode = 10	0.93	0.94	0.89	0.87	0.94	0.92	0.89	0.9	0.91	0.76	0.84	0.8	0.92	0.93	0.94	0.91	0.91	0.94	0.8	0.89	0.94	0.894
kerode = 15	0.93	0.94	0.89	0.87	0.94	0.93	0.89	0.9	0.91	0.76	0.84	0.8	0.92	0.93	0.94	0.92	0.92	0.94	0.8	0.89	0.94	0.895
kerode = 20	0.93	0.94	0.89	0.87	0.94	0.92	0.89	0.9	0.91	0.76	0.83	0.79	0.92	0.92	0.93	0.9	0.91	0.94	0.8	0.89	0.94	0.891
kerode = 25	0.93	0.94	0.89	0.87	0.94	0.92	0.89	0.9	0.91	0.76	0.83	0.79	0.91	0.92	0.93	0.91	0.92	0.94	0.8	0.89	0.94	0.892
kerode = 30	0.93	0.94	0.89	0.87	0.94	0.92	0.89	0.9	0.91	0.76	0.82	0.79	0.9	0.91	0.92	0.89	0.9	0.94	0.8	0.88	0.93	0.887
kerode = 35	0.93	0.94	0.89	0.87	0.94	0.92	0.89	0.9	0.91	0.75	0.81	0.79	0.89	0.91	0.92	0.9	0.9	0.93	0.78	0.87	0.93	0.884

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Table 3. Accuracies for occlusal images with selection of different window sizes for dilation.

image name	1	2	3	4	5	6	7	8	9	average
kdilate = 5	0.9	0.93	0.92	0.8	0.92	0.89	0.86	0.88	0.87	0.886
kdilate = 7	**0.9**	**0.93**	**0.92**	**0.8**	**0.92**	**0.89**	**0.87**	**0.88**	**0.87**	**0.887**
kdilate = 10	0.9	0.93	0.92	0.8	0.92	0.89	0.87	0.88	0.87	0.887
kdilate = 12	0.9	0.93	0.92	0.8	0.92	0.89	0.87	0.88	0.87	0.887

Table 4. Accuracies for occlusal images with selection of different thresholds T_max for edge detection.

image name	1	2	3	4	5	6	7	8	9	average
thresh = 20	0.9	0.93	0.89	0.8	0.92	0.89	0.87	0.88	0.87	0.883
thresh = 23	0.9	0.93	0.92	0.8	0.92	0.89	0.87	0.88	0.87	0.887
thresh = 25	**0.9**	**0.93**	**0.92**	**0.8**	**0.92**	**0.89**	**0.87**	**0.88**	**0.89**	**0.889**

Table 5. The angle of crown preparation computed by the proposed method and experts.

Image number	21	20	19	18	17	16	15	14	13	12	11	10	Average
Ground truth angle	35.1	44.32	32.3	31.1	37.5	25.2	49.1	51	31.8	44.1	54.3	35.4	-
Computed angle	45.95	52.66	41.22	38.1	46.62	32.62	54.73	60.1	40.39	42.28	47.5	37.9	-
Error	-10.85	-8.34	-8.92	-7	-9.12	-7.42	-5.63	-9.1	-8.59	1.82	6.8	-2.5	-
Absolute Error	10.85	8.34	8.92	7	9.12	7.42	5.63	9.1	8.59	1.82	6.8	2.5	7.17

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Table 6. IOU for segmentation.

Image number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	average
IOU	0.93	0.94	0.89	0.87	0.94	0.93	0.89	0.9	0.91	0.76	0.84	0.8	0.92	0.93	0.94	0.92	0.92	0.94	0.8	0.89	0.94	**0.897**

Table 7. IOU for internal and external contour segmentation.

Image number	1	2	3	4	5	6	7	8	9	average
External contour	0.96	0.95	0.86	0.94	0.96	0.97	0.91	0.92	0.95	0.93
Internal contour	0.9	0.93	0.92	0.8	0.92	0.89	0.87	0.88	0.87	0.887

Fig. 1. Block diagram of the proposed method.

Fig. 2. (a)First Image. Facial image before and (b) Second Image, after crown preparation.

Fig. 3.Facial Image with registration of FirstImg and SecondImg.

Fig. 4. (a)Source occlusal image and (b)Selected ROI.

Fig. 5. A Binary occlusal image achieved from thresholding in HSV color domain.

Fig. 6. The result of canny edge detector on selected ROI from occlusal image.

Fig. 7. Effect of erosion operation. (a) before and (b) after erosion.

Fig. 8. Effect of dilation operation. (a) before and (b) after dilation

Fig. 9. Contour segmentation in Occlusal image. (a) Segmented contours by the proposed method, (b) exterior contour segmented by expert and (c) interior contour segmented by expert.

Fig. 10. Contour segmentation in Facial image. (a) Segmented contours by the proposed method, (b) segmented contour by expert.

Fig. 11. Corresponding points located in interior and exterior contours.

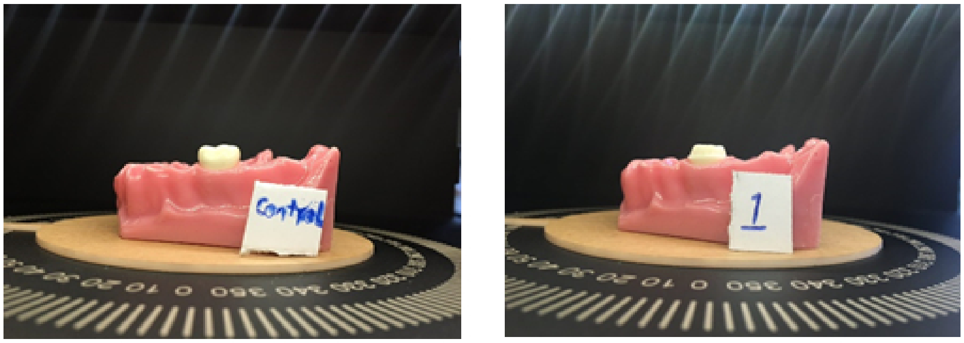
Fig. 12. Crown preparation with differences higher than threshold.

Figure 13. Crown preparation angle in facial image.

Fig. 14. Segmented contours by the proposed method (left image) and expert (right image) in 8 sample Facial images.

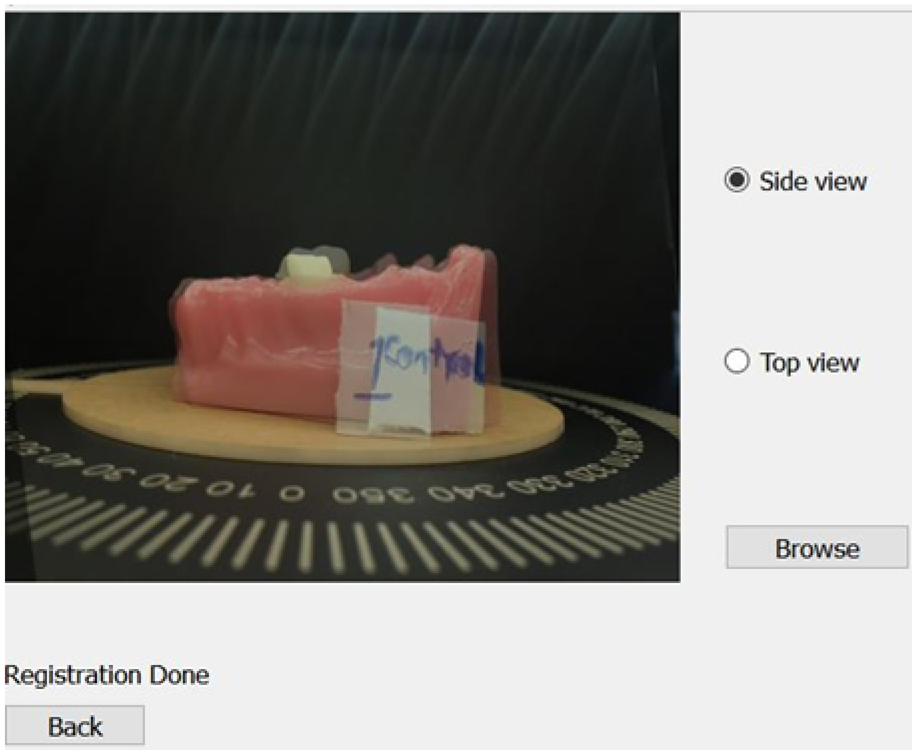
Fig. 15. Segmented contours by the proposed method (left image) and expert (right image) in 8 sample occlusal images.

Block diagram of the proposed method.

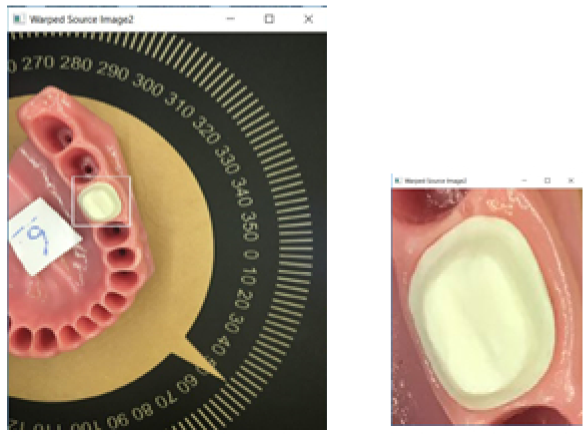


(a) (b)

(a)First Image. Facial image before and (b) Second Image, after crown preparation.



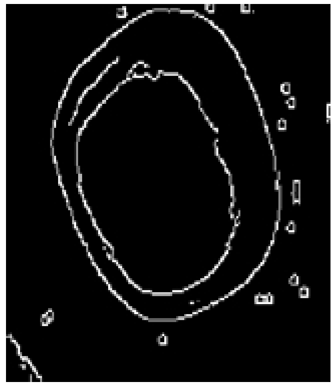
Facial Image with registration of FirstImg and SecondImg.



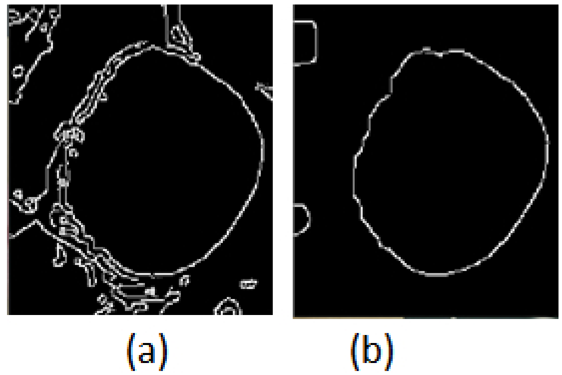
(a) (b)

(a)Source occlusal image and (b)Selected ROI.

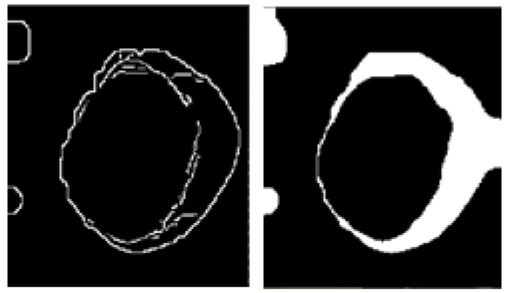
A Binary occlusal image achieved from thresholding in HSV color domain.



The result of canny edge detector on selected ROI from occlusal image.

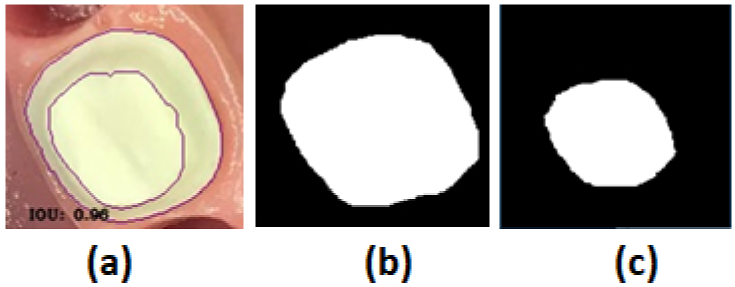


Effect of erosion operation. (a) before and (b) after erosion.

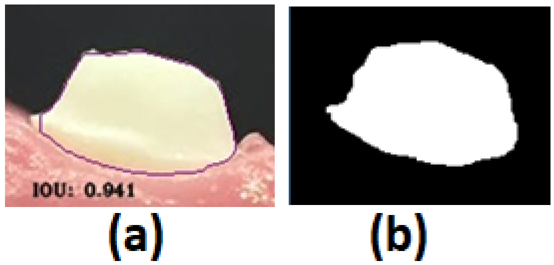


(a) (b)

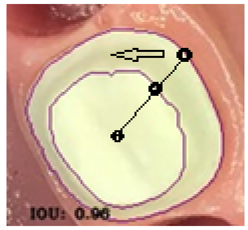
Effect of dilation operation. (a) before and (b) after dilation



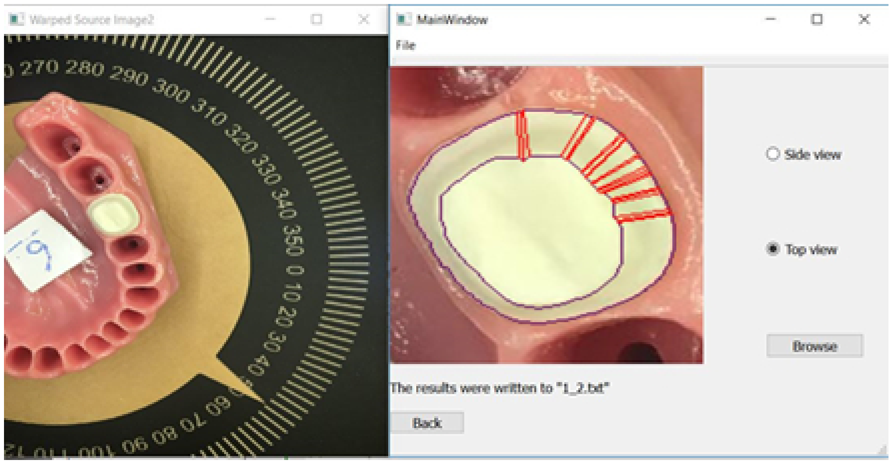
Contour segmentation in Occlusal image. (a) Segmented contours by the proposed method, (b) exterior contour segmented by expert and (c) interior contour segmented by expert.



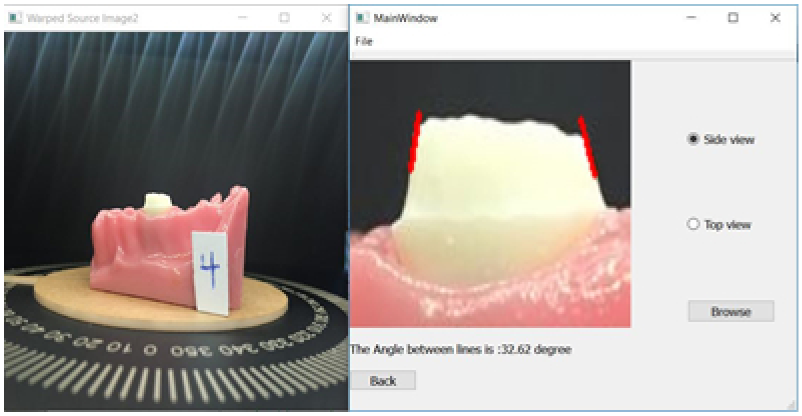
Contour segmentation in Facial image. (a) Segmented contours by the proposed method, (b) segmented contour by expert.



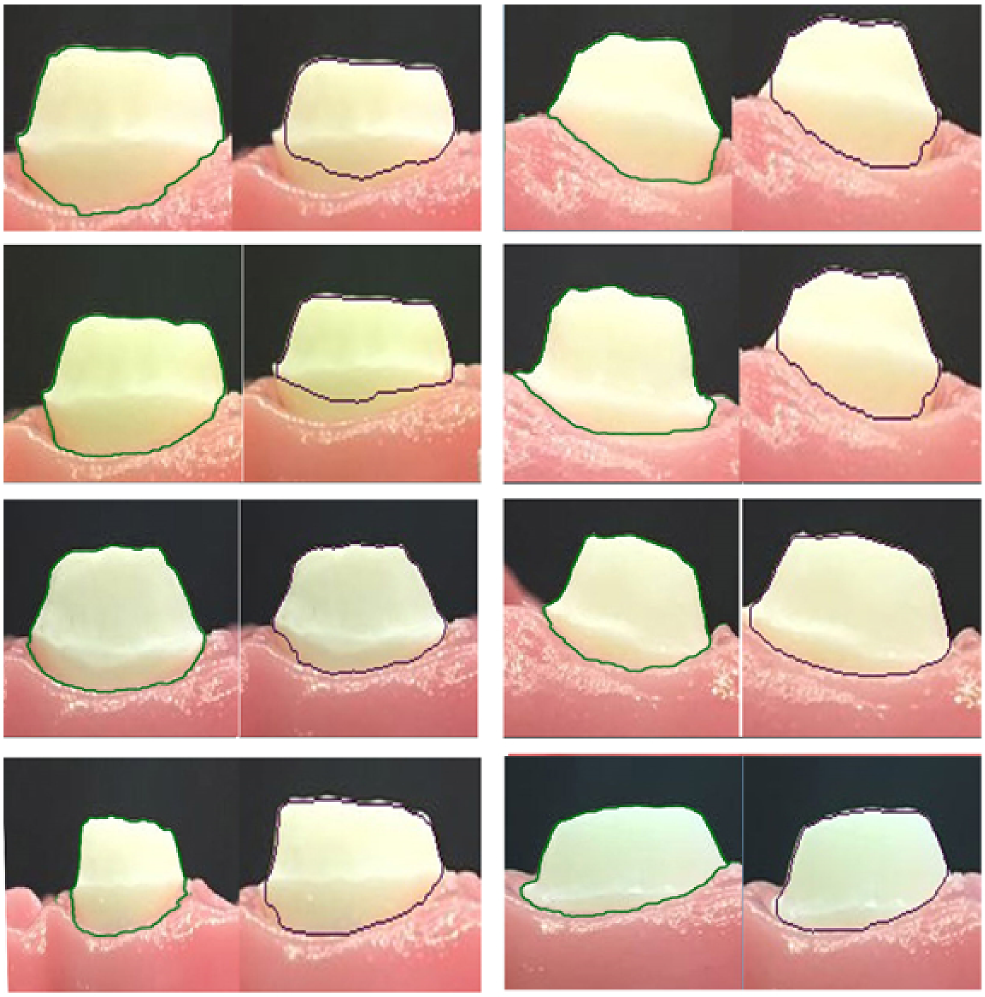
Corresponding points located in interior and exterior contours.



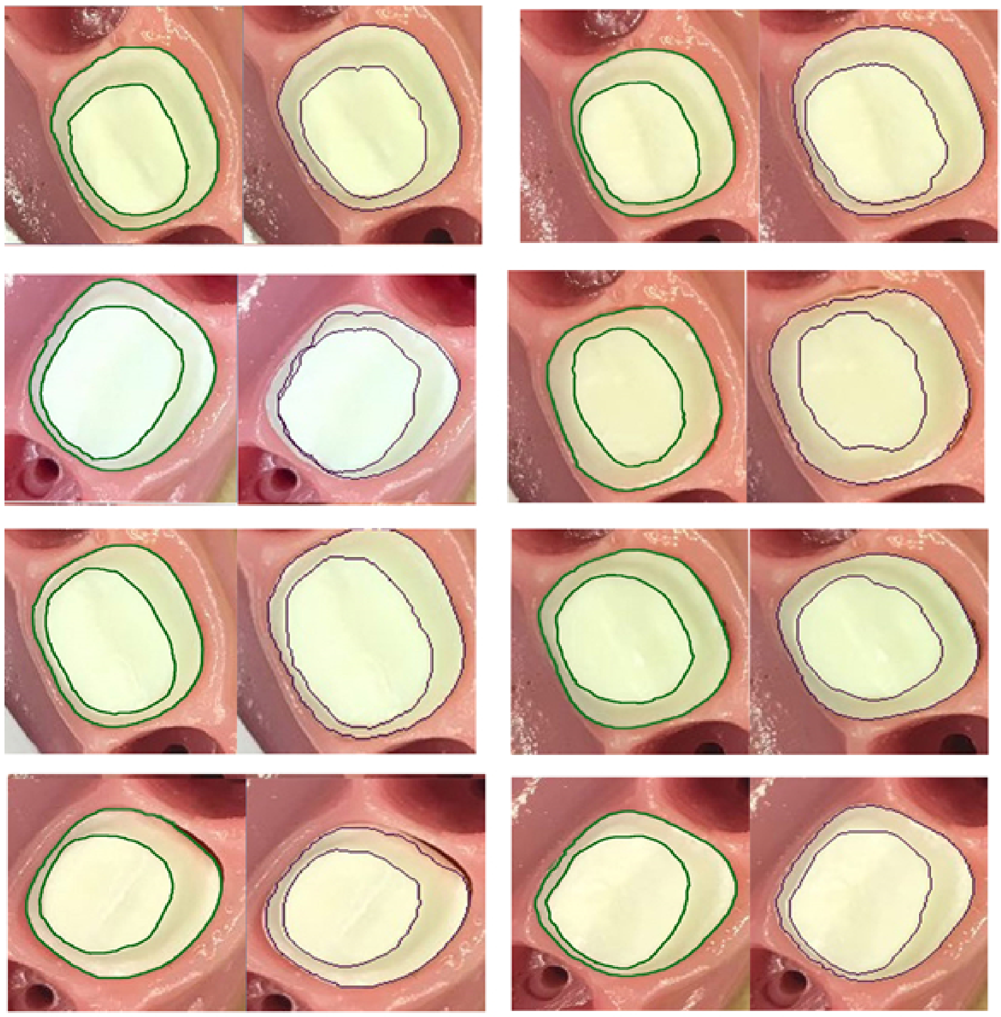
Crown preparation with differences higher than threshold.



Crown preparation angle in facial image.



Segmented contours by the proposed method (left image) and expert (right image) in 8 sample Facial images.



Segmented contours by the proposed method (left image) and expert (right image) in 8 sample occlusal images.