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Skeletal Approach to Mandible Reconstruction Represented as an Image

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ABSTRACT

Mandible or facial bone reconstruction is a serious challenge in craniomaxillofacial surgery. Considering the complex shape and structure of the mandible, careful presurgical planning or availability of objective methods to analyse the patient mandible is necessary to achieve predictable outcomes. It has become evident that methods that can retrieve back the exact shape and structure of the mandibular defect across any anatomical location of the mandible are required. Skeletons, a dimensionally reduced version of the shape, are an important descriptor capable of capturing the most relevant features. In this paper, a technique to retrieve the shape of the mandible from its skeleton properties, by comparing it to the skeleton of a mandible with no defects, also called template mandible has been addressed. It is also employed to correct the mandibular structure for the type of discontinuity in it, to obtain a reconstructed mandible. This will enable to look at how the defect or the discontinuity in the structure will appear after reconstruction in the presurgical phase. Moreover, this kind of analysis will provide a good basis for planning the reconstruction technique to be used clinically. Width calculation for structural shape like mandible has also been implemented. Imaging a mandible with segmental defect and performing its reconstruction validate the results. In this work, an image of the mandible is used as a template mandible.

Keywords: mandible reconstruction, skeleton, shape retrieval.

1. INTRODUCTION

The mandible is a unique bone and is very important for a number of reasons - airway stability as it supports the tongue base, speech, defining the features and shape of the lower face, mastication (chewing) etc. Mastication and speech are the principle functions of jaw activity. Mandible can get affected in one of the following ways - when portion of it has to be removed because of cancerous growth or damaged/broken due to an accident. Accurate reconstruction of the mandible can help in regaining some of the lost features such as the speech or facial structure. However, the unique anatomies of the mandibular arch, mandibular midline etc. have made reconstruction difficult. The anatomy is located near the skull base and complications of the reconstruction can be devastating. Therefore, for successful reconstruction of the mandibular defect plays a vital role.

1.1. Mandible Structure and Defects

The mandible lower jaw is one of the bones that comprise the skull [5]. Important features include the alveolar process the tooth bearing area, the condyle, the coronoid process, and the mandibular symphysis, where the two halves of the mandible join, at the chin. Anatomical regions of the mandible include the body, the angle, and the ramus, as illustrated in Fig. 1. It exhibits bilateral symmetry. The mandibular system, composed of bone, teeth, ligaments and muscles, is a sophisticate combination of anatomic structures and is related to the physiological phenomena of bone remodeling resorption and apposition that may influence the reconstruction and prosthetic rehabilitation [13].

Mandibular morphology involves both size and shape [9]. Shape refers to the structure independently from its orientation and size to dimensions. The combination of various muscular and external loading forces on the mandible is unique compared to long bones and a clear understanding of the unique mandibular structure is important for mandibular reconstruction techniques. This is due to the fact that, unlike long bones in the body, the orientation of the stiffest direction in the mandible is perpendicular to the direction of loading during function. Also, mandible is a V-shaped bone as shown in the Fig. 2.

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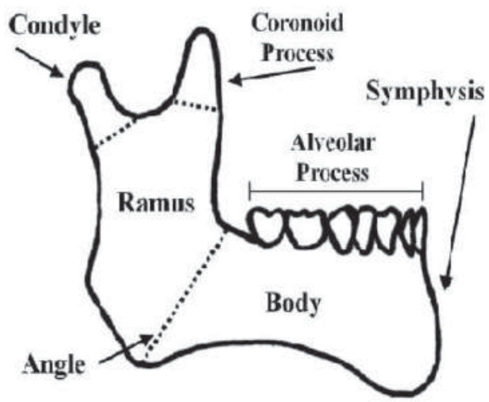

Fig. 1: Anatomy of a mandible.

Fig. 2: V-shape of the arc.

The first goal in mandibular reconstruction is accurate classification of the defect and an understanding of the likely resultant functional deficits. Bony mandibular defects are classified by the amount of hard tissue loss specific to an anatomic region [7]. Cantor and Curtis [11] classified mandibular defects into six classes as shown in Fig. 3. Class I mandibular defects involve the alveolus, but with preservation of mandibular continuity. Class II defects involve loss of continuity distal to the canine. Class III involves loss up to the mandibular midline region. Class IV deficiencies involve the lateral aspect of the mandible but are augmented to maintain pseudo articulation of bone and soft tissue in the region of the ascending ramus. Class V involves the symphysis and parasynthesis regions only, augmented to preserve bilateral temporomandibular articulations. Class VI is similar to class V, except that mandibular continuity in not restored. Another classification can be found in [6].

1.2. Skeletons

In shape analysis, skeleton of a shape is a thin version of that shape that is equidistant to its boundaries. The

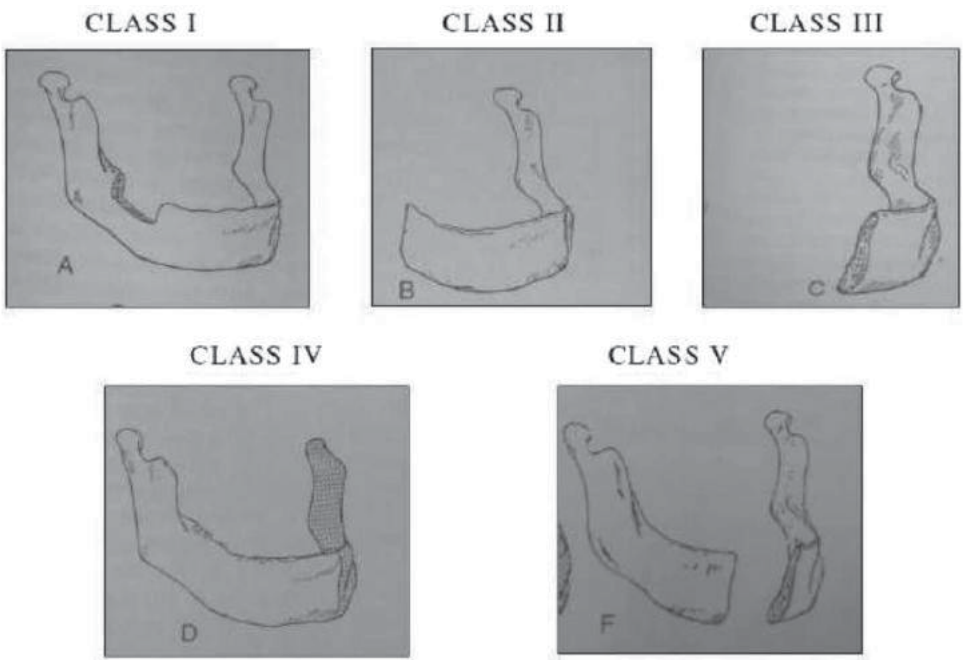

Fig. 3: Classification of defects.

skeleton usually emphasizes geometrical and topological properties of the shape, such as its connectivity, topology, length, direction, and width. Together with the distance of its points to the shape boundary, the skeleton can also serve as a representation of the shape they contain having all the information necessary to reconstruct the shape.

The skeleton is useful because it provides a simple and compact representation of a shape that preserves many of the topological and size characteristics of the original shape. Thus, for instance, we can get a rough idea of the length of a shape by considering just the end points of the skeleton and finding the maximally separated pair of end points on the skeleton. Similarly, we can distinguish many qualitatively different shapes from one another on the basis of how many 'triple points' there are, i.e. points where at least three branches of the skeleton meet. Various different variants of skeleton can also be found, including curve skeleton, straight skeletons, morphological skeletons, canonical skeleton and skeletons by influence zones also known as Voronoi diagram, medial axis transform (MAT). For details of various skeletons, please see [1].

2. CURRENT TRENDS

2.1. In Pre-surgical Planning

Currently, in presurgical planning involving the reconstruction of mandibular defect, the three dimensional model of the mandible is generated from the CT data premise [16], and it is analysed for the placement of device and for design of the bone plates. The use of image processing techniques have been largely limited to contrast enhancement and different segmentation techniques, and no analysis is done on correcting the defect. In CAD/CAM assisted mandibular reconstruction [10], the surgical time was significantly reduced by performing a pre surgical planning on the three dimensional model of the mandible and via CAD/CAM assisted design of the bone plate, which correctly fits the discontinuity location. Deviation were still reported from predicted outcomes.

Due to the complex structure of the mandible, the use of the conventional metric approach, consisting of distances, angles, and ratios etc. can be considered appropriate for only the simplest morphologies [4]. Thus arises the need for more objective methods for analysis, which can even be coupled with the above mentioned approaches to provide a better analysis of the mandible for performing reconstruction.

2.2. In Clinical Repair Techniques

Mandibular reconstruction after cancer removal using a vascularized fibula free flap [8] is currently a standard treatment option. Primary reconstruction offers the best opportunity to achieve the optimal aesthetic and functional results [10]. This requires prolonged surgical time or more aggressive surgical procedures as microvascular free tissue transfer is technically difficult and invasive with significant donor site morbidity.

An alternate approach is called transport Distraction Osteogenesis (TDO). The goal of TDO is to restore bony continuity through the use of in-situ bone in an attempt to create an anatomically correct regenerate that is better than bone grafting or revascularized free-tissue transfer. The technique of TDO where the transport bone segments are slowly moved so that new bone is regenerated has been used to reconstruct continuity defects by regenerating bone and soft tissue. The power of TDO lies in its ability to recreate new bone and soft tissues. Aesthetic goals include restoring normal appearance of the reconstructed soft tissues, facial symmetry, restoration of the dental arch, and preservation of the lower facial dimensions [12]. Rendering pre surgical planning an important step for performing TDO.

3. MOTIVATION AND METHODOLOGY

Motivation for this work came from the need for an objective method required for pre surgical planning of reconstruction process. Reconstruction of the mandibular defects is a challenging problem when presented across the midline. The arch architecture of the mandibular midline poses a challenge to duplicate with any modality of reconstruction. Thus arising the need for a process, which can help in the analysis of patient's anatomy for knowing the extent and location of the segmental defect and provide better analysis by showing the reconstruction of the missing portion or correcting the type of mandibular defect.

The focus of this work is to present a methodology by which we can locate and extract the region of discontinuity in the mandibular structure. The reconstruction of the mandibular defect has been performed by deducing its skeleton. The originality of this paper lies in applying the skeletal concepts to mandible reconstruction. In this work, Medial Axis transform (MAT) [14] of the shape and the associated radius along with the corresponding details of the template mandible (which is without any defect) has been performed. The same portion from the template mandible replaces the missing portion of the mandible to be reconstructed by fitting the region of discontinuity by the skeleton of the same anatomical region from the template mandible. MAT also enables to compute the width at a point on the mandible. Imaging a mandible with segmental defect and reconstructing it based on the same template mandible validate results. The various techniques used for the analysis of the mandible image are shown in flowchart (Fig. 4).

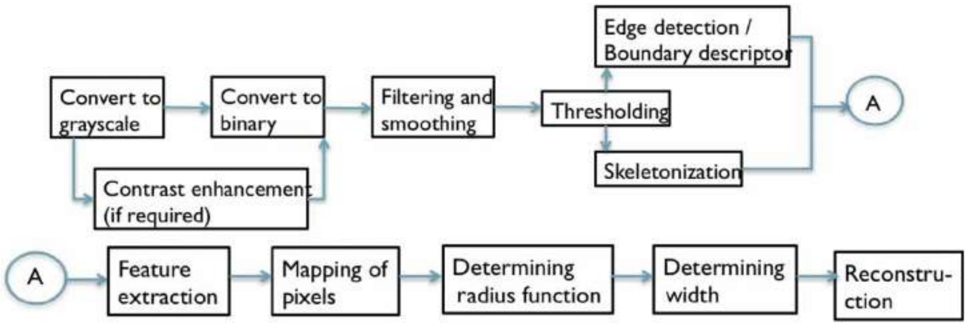

Fig. 4: Methodology for reconstruction.

4. IMAGE PROCESSING DETAILS

4.1. Processing Input Images

The RGB image is converted to gray scale intensity image by eliminating the hue and saturation information while retaining the luminance. The image does not usually present the desired object contrast. Obtaining the histogram of the intensity values and performing histogram equalization can adjust the contrast. The gray scale intensity image is then converted to binary image. The level of the image is determined by a threshold value. Image filtering is a then applied for noise removal and resolution recovery. The goal of the filtering is to compensate for loss of detail in an image while reducing noise in the image.

Smoothing is the done by the application of the Gaussian filter [3]. Image is thresholded so that the region of interest can be isolated from the background for further analysis. It is usually obtained by multiplying the binary image with the initial image.

4.2. Edge Detection and Boundary Descriptors

There are two ways of image analysis via edge detection:

- Based on the discontinuities.
- Based on the similarities of structures in an image.

In mandible images with segmental defect, the discontinuity or feature extraction from detected edge finds more applications. This type depends on the detection of discontinuities by finding edges. In addition, a threshold is applied in order to detect edges above defined grey-scale intensity to obtain the optimum edge with minimal noise and with features required for further processing. In this work, the canny method is applied in order to detect edges in an image (Fig. 5).

When dealing with region boundaries, descriptors like Fourier Descriptors (FD) are very useful to omit the redundant points on the region boundary.

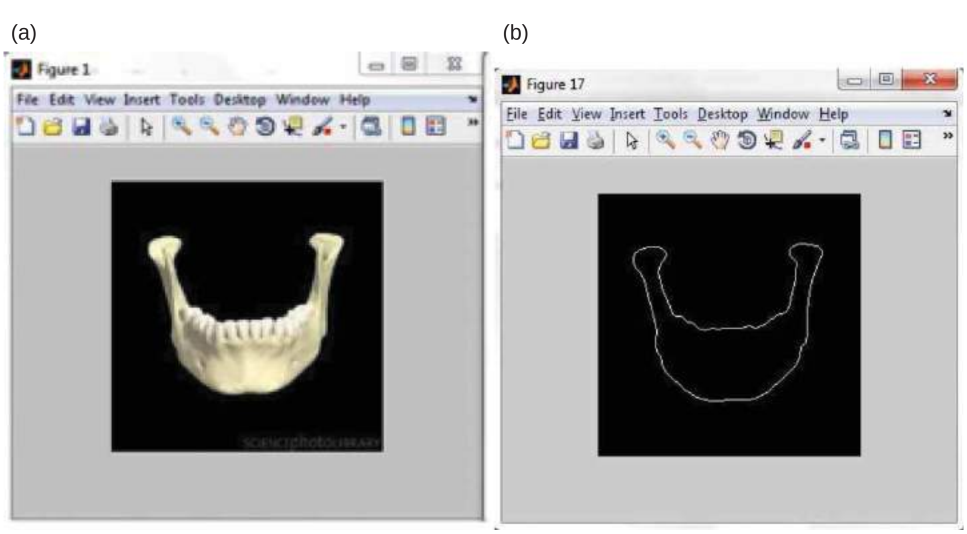

Fig. 5: (a) Image and (b) Edge detection.

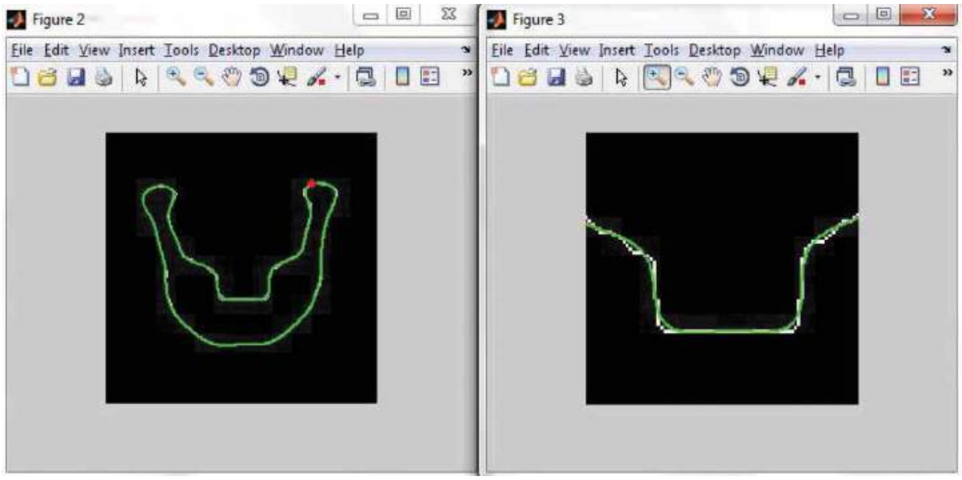

Fig. 6: Result of Fourier descriptor.

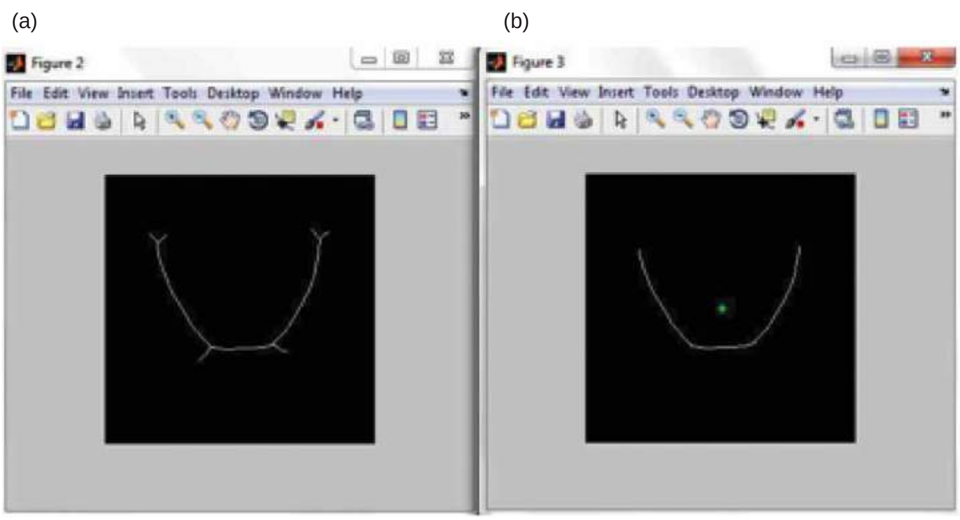

Fig. 7: (a) Skeleton b) Skeleton after despurring or pruning.

FD makes the region boundary suitable for further analysis like feature extraction. The high frequency components account for fine details, and low frequency components determine global shape. Thus global shape is retained for the detected region boundary or edge of the mandible. Fig. 6. [From left to right] a) Green boundary represents the application of FD on the boundary of mandible with segmental defect and the red dot is the start point of region boundary tracing b) Zoomed view.

4.3. Skeletonization

An important approach for representing the structural shape of a planar region is to reduce it to a skeleton. This reduction may be accomplished via a thinning also called morphological erosion. The skeleton of a region may be defined via the medial axis transform (MAT). The medial axis transform (MAT) is a process for reducing foreground regions in a binary image to a skeletal remnant that largely preserves the extent and connectivity of the original region while throwing away most of the original foreground pixels. Despuring or pruning is done after skeleton is obtained to remove the unwanted branching, which may interfere with the recognition process. The skeleton obtained after despuring or pruning is called the canonical skeleton. The process is shown in the Fig. 7.

5. FEATURE EXTRACTION

Feature extraction is used as an approach to visualization aiming at automatic recognition of important features that can be structures, objects, or regions. Rather than leaving the recognition of the interesting features entirely to the visual inspection by the user, this task is performed automatically. The extracted features are characterized by quantitative descriptions or attributes. The features are directly related to anatomical location of the region. Thus making it possible to look at type of discontinuity or defect in the structure.

In this work, the algorithm used for the implementation of feature extraction is based on the idea that, wherever a defect or a discontinuity will be present, there will be a change in the gradient. Normal mandible without discontinuity will not show a sudden change in gradient at consecutive pixel location. The detected edge of the mandible can be traversed in any region, like the body of the mandible, mental symphysis, the ramus of the mandible and based on the region we can detect the discontinuity. The points showing the maximum gradient change were extracted and there location determined the position of the discontinuity in that particular region of the mandible. Fig. 8 shows the discontinuity region depicted by the maximum gradient change points.

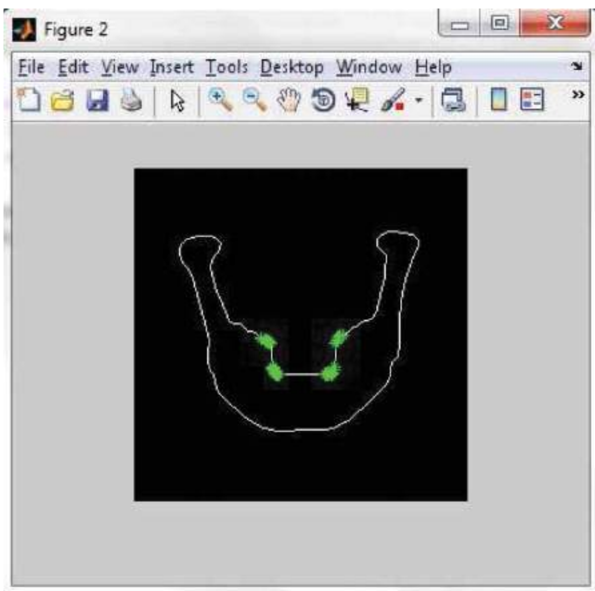

Fig. 8: Discontinuity region.

6. MAPPING OF THE PIXELS

Using operations like filtering and boundary descriptors, we omit the pixels on the region boundary, which represent sharp edges, and hence slightly changing the shape of the region boundary from the original edge detected of the mandible. To map the discontinuity points on the original boundary, we check the neighborhood connectivity of pixels. Four neighbors (N4(P)) or eight neighbors of P (N8(P)) are the commonly employed ones.

Two pixels are connected if they are neighbors and their gray levels satisfy some specified criterion of similarity. For example in a binary image two pixels are connected if they are either N4 connected or N8 connected and have same value of 0 or 1 for a binary image. In this work, the boundary points of the image after feature extraction are mapped back on the initial boundary based on the N8 neighborhood connectivity of the pixels and having the value one, as both the pixels represent white or switched on pixels of the region boundary. Fig. 9 shows the mapping of pixels based on their neighborhood connectivity.

7. DETERMINATION OF THE RADIUS FUNCTION AND WIDTH

The chosen method to find the radius associated with each pixel point of the skeleton was the distance transforms (DT). In a DT, on a shape, each pixel is labeled with its distance to the background. It is also the radius of the largest disk in the shape centered on that pixel. The distance transform provides a metric or measure of the separation of points in the image. The radius for each pixel point on the skeleton is

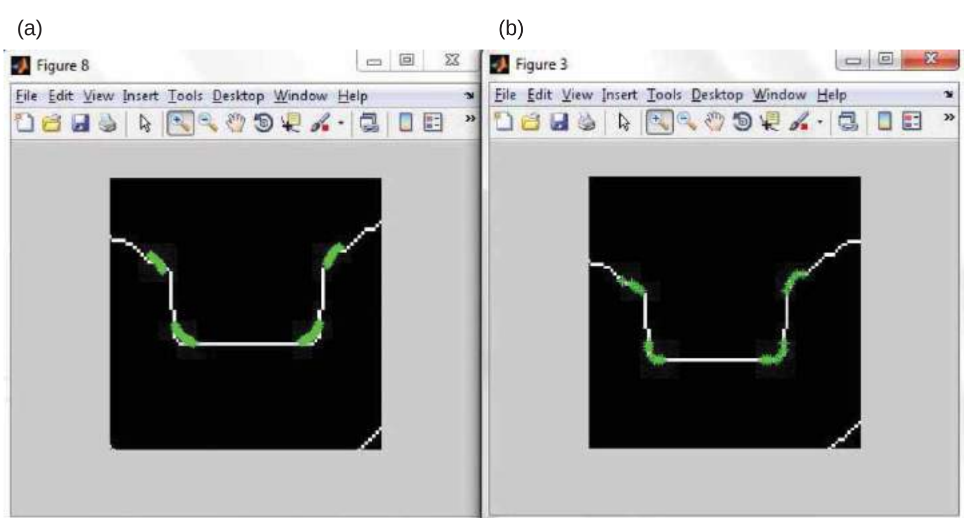

Fig. 9: (a) Points (b) Mapping of points.

defined as the radius of the maximum inscribed circle for the shape centered at that pixel.

The width at a particular skeleton point is determined, by finding out the points of tangency of the disk centered at that skeleton point to the region boundary. The distance between the two points of tangency will give us the width of the mandible for that region. The same process is repeated for all skeleton points to determine the mandible width from one anatomical end to the other, and the concept is illustrated by considering a simple ellipsoidal shape (Fig. 10), showing the width at different points on the skeleton.

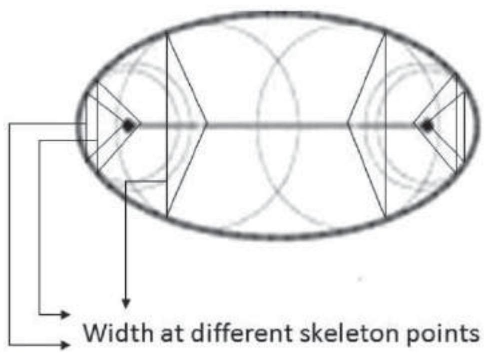

Fig. 10: Width at a point.

8. RECONSTRUCTION FOR MANDIBULAR DEFECT

The reconstruction of the mandibular defect is performed by comparing the radius function of the mandible with defect to the radius function of the template mandible. The region where the radius function was deviating in comparison to the template could be located. As every radius is associated to a point on the skeleton, the skeleton for the discontinuity region or the region of defect on the mandible was fitted with the skeleton of the template mandible for the same region.

Each point on the skeleton can be mapped back to the original region boundary from which it is deduced. The defect is then corrected or reconstructed by using a method that reverses the process of skeletonisation or called as Inverse Distance Transform.

9. RESULTS AND DISCUSSION

The implementation of the methodology has been done by using MATLAB [2] and the IPT, which provide a wide range of advanced image processing functions and interactive tools for analyzing digital images. The interactive tools allowed us to perform morphological operations such as skeletonisation, edge detection and noise removal, region-of-interest processing, smoothing and filtering, Fourier descriptors and distance transform on digital images of the mandible [15].

9.1. Results for Template Mandible

The radius function for the template mandible, comparing to which the reconstruction was performed is shown in the Fig. 11.

9.2. Results for Reconstruction of Different Type of Mandibular Defects

9.2.1. Class I type defect

Class I mandibular defects involve the alveolus, but with preservation of mandibular continuity, class I type mandibular defect are along the mandibular midline, anywhere on the left and the right half of the dental arc, and hence to reduce the computational process only the mandibular midline is considered.

The results for all the defects are captioned in the following manner - a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible. Fig. 12 shows results for reconstruction of mandible with class I defect on dorsal side. Fig. 13 shows results for reconstruction of mandible with class I defect on ventral side.

9.2.2. Class II type defect

Class II type mandibular defect involve loss of continuity distal to the canine. Fig. 14 shows the reconstruction of the class II type mandibular defects.

9.2.3. Class III type defect

Class III type mandibular defect involves loss of continuity, up to the mandibular midline region. Fig. 15 shows the reconstruction of the class III type mandibular defects.

Also, the reconstruction of a discontinuity classified in class III but which involves the loss of the whole mandibular body except the ramus, and the continuity of the mandible is only maintained by the soft tissue is shown in Fig. 16, this type of defect is generally observed in osteoradionecrosis cases.

9.2.4. Class IV type defect

Class IV type mandibular defect involves the loss of ascending ramus, the lateral aspect of the mandible but are augmented to maintain pseudo articulation of

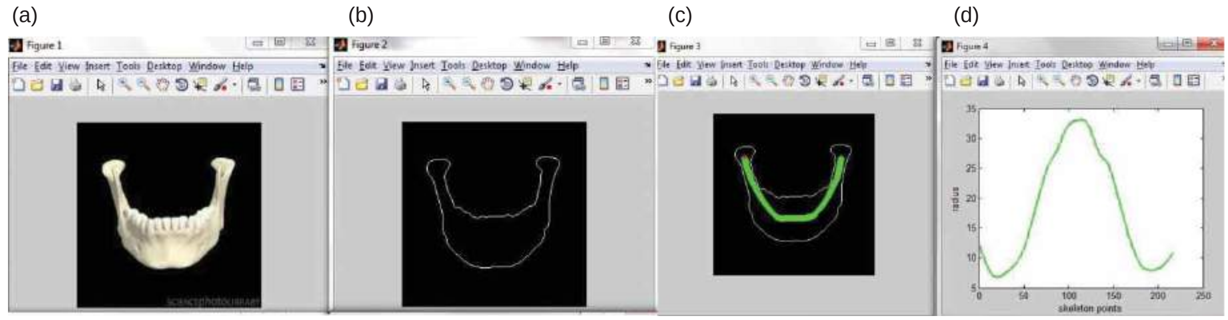

Fig. 11: a) The template mandible b) The detected edge of the template mandible c) The detected edge with the skeleton in green d) The radius function.

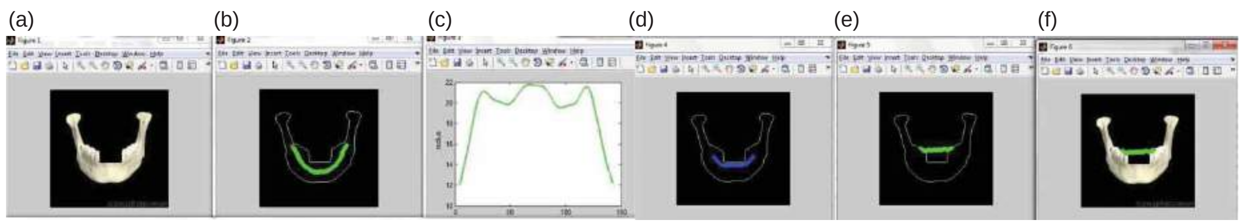

Fig. 12: Class I defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

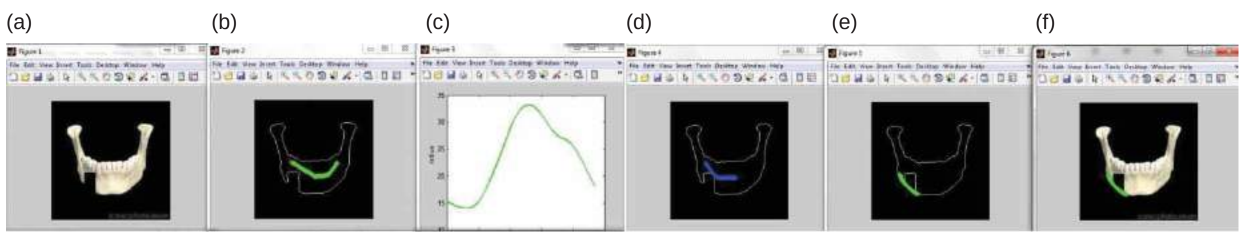

Fig. 13: Class I defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

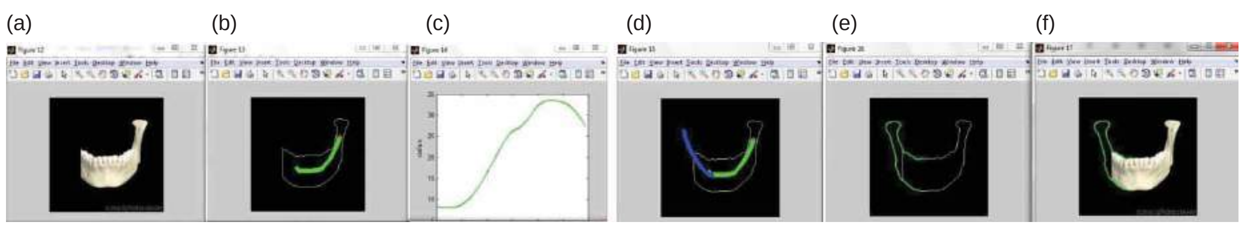

Fig. 14: Class II defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

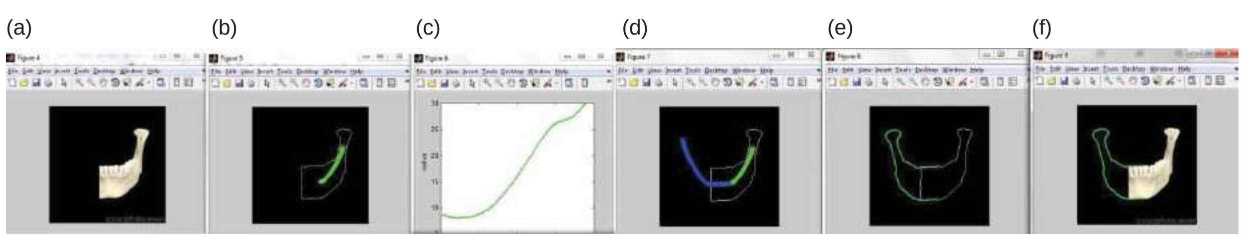

Fig. 15: Class III defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

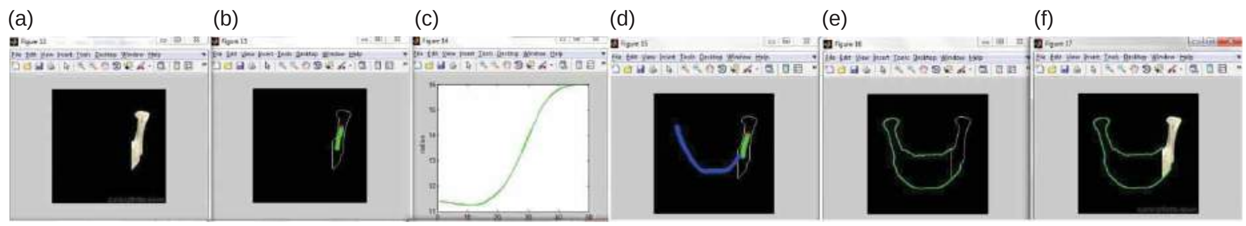

Fig. 16: Class III defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible

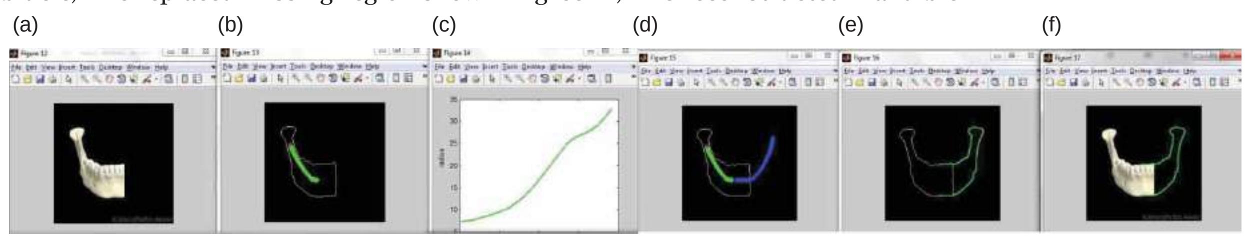

Fig. 17: – Class IV defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

bone and soft tissue in the region of the ascending ramus. Fig. 17 shows the reconstruction of the class IV type mandibular defects

9.2.5. Class V type defect

Class V type mandibular defect involves the loss of mental symphysis region. The Fig. 18 shows the reconstruction of the class V type mandibular defect.

9.3. Width Determination

The width for the mandibular structure is determined by finding the intersection of the radius of the maximal disk centered at skeletal points, to the region boundary and then calculating the distance between the points obtained on the region boundary. The results for the width variation of the mandible along the mandibular arch are shown in the Fig. 19.

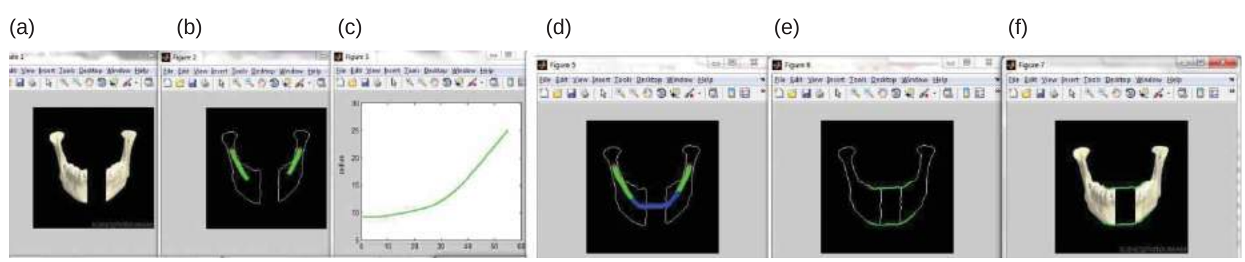

Fig. 18: – Class V defect a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

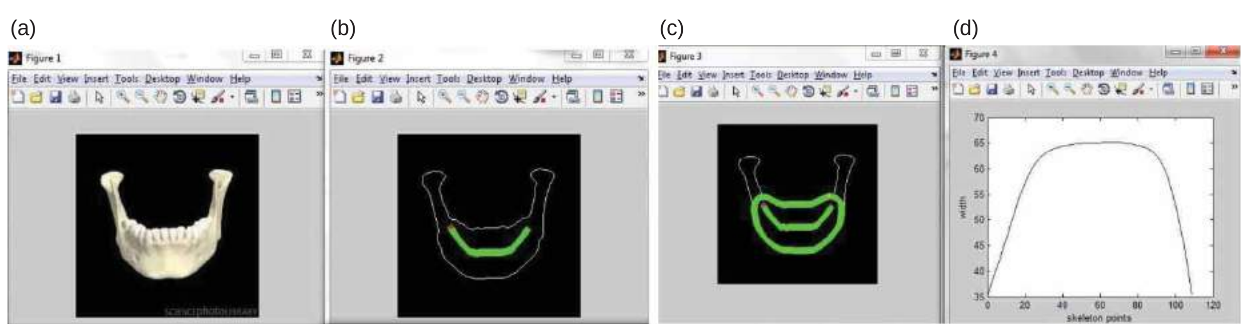

Fig. 19: a) The template mandible b) The detected edge with the skeleton c) The contour in green surrounding the skeleton d) The width function for all skeleton points.

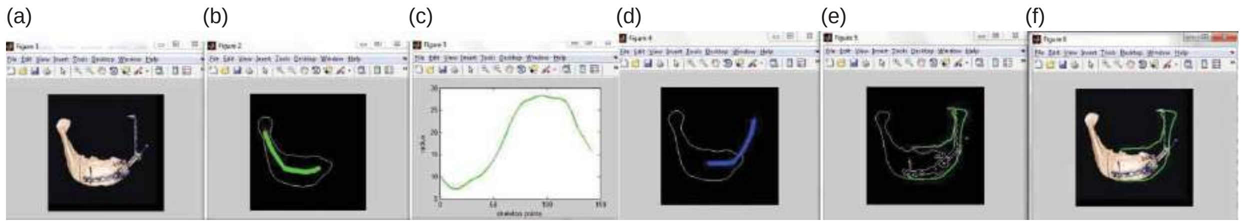

Fig. 20: Validation of the result a) Mandible with defect b) The detected edge with the skeleton in green c) The radius function for all skeleton points d) The region of defect fitted with the skeleton of the template mandible shown in blue e) The replaced missing region shown in green f) The reconstructed mandible.

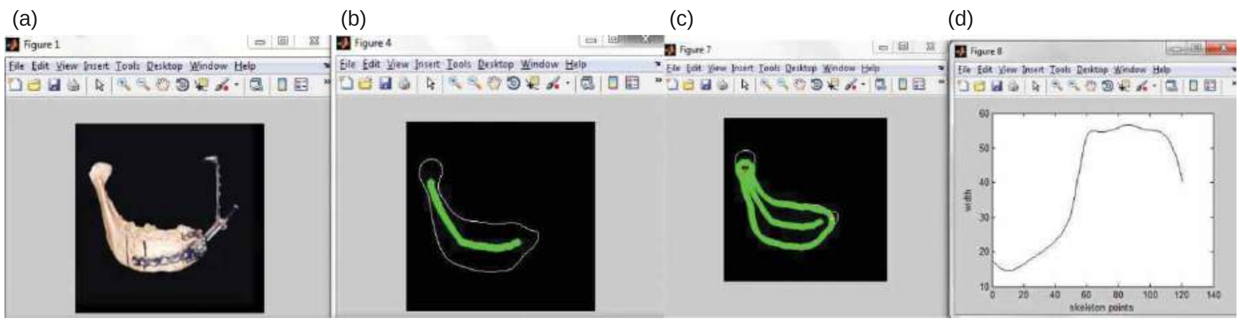

Fig. 21: a) The template mandible b) The detected edge with the skeleton c) The contour in green surrounding the skeleton d) The width function for all skeleton points.

9.4. Validation of the Results

It was possible to reconstruct a mandible with defect by the methodology presented in this work. Reconstruction was performed on an image of the mandible that had a defect involving the loss of the complete right mandibular arc. The results of the mandibular reconstruction and the width determination are as shown in Figs. 20 and 21.

9.5. Discussion

Reconstruction of the mandibular defect is a challenging problem, when presented across the midline of the mandible. The arch and architecture of the mandibular midline poses a challenge to duplicate with any modality of reconstruction. It has become evident that methods that can retrieve back the exact shape and structure of the mandibular defect across any anatomical location of the mandible are required. Therefore an approach was needed which can address the complexity of the shape and structure of the mandible. The approach presented in this work will aid greatly in the planning of the reconstruction process as skeleton extracts a significant percentage of the informational content that resides in complex morphological forms. It also enables us to describe efficiently the exact shape and size of complex forms.

For shape retrieval, skeleton plays a major role in object representation and recognition. Skeleton contains both the shape features and topological structure of the object. The skeleton of the mandibular structure is a thin version of the mandible, which is equidistant from its boundaries. Each pixel point of the skeleton has information about the corresponding point on the boundary or detected edge of the mandible and emphasizes connectivity, topology and width. Together with the distance of each skeleton point to the boundary of the mandibular shape, the skeleton serves as a representation of the shape thus making it possible to retrieve or reconstruct the shape.

Currently in presurgical planning, the width measurement for mandibular structure is determined based on the slice thickness of the modality used to image the patient's mandible [4]. The method doesn't seem very potent considering the shape of the mandible. When viewed in the sagittal plane the inferior border of the mandibular corpus is not parallel to the maxillary occlusal plane. Thus width cannot be determined on the basis of conventional metric approach.

Thus a more objective method based on the radius information obtained for each skeleton point was used to determine the width of the mandible. Each skeleton point is center to the maximal disk inscribed in the shape centered at that point, by finding the intersection point of the radius with the region boundary and calculating the distance between the points obtained on the boundary, width was determined giving a more accurate determination of the width considering the shape and size features of the mandible at the same time.

The use of template mandible information for performing reconstruction of the missing region gives an advantage to this approach. As a more regular surface of the reconstructed defect can be obtained, which closely mimics the exact shape, as it would have been without any defect. Thus enhancing the ability to know the extent and the type of defect with respect to patient's anatomy, and aiding in deciding for the type of clinical repair technique to be used. The current methods in presurgical planning are not addressing the shape and structural features of the mandible and thus deviating from planned results in cases where reconstruction of complex anatomical regions like mandibular midline is involved.

9.6. Limitations

- The methodology presented in this work, involves the detection of the edge of mandibular structure. Therefore, the results might vary with different edge detection techniques and since a threshold has to be determined for edge detection, the threshold might vary from image to image.
- The determination of threshold for edge detection is more of an experimental process, where different thresholds are tested for the type of results they are giving.
- The selection of a particular threshold for edge detection depends upon the features you want to be prominent in the detected edge.

10. CONTRIBUTIONS, FUTURE WORK AND CONCLUSIONS

This work represents one step in a wider protocol for mandibular reconstruction. A new method is presented for mandibular reconstruction based on the deduced skeleton of the shape, and then identifying the location of the defect on the mandibular structure and performing its reconstruction by matching the similar portion on the template mandible. The analysis and planning in presurgical phase on a reconstructed mandible corrected for the discontinuity, will aid to a greater extent in understanding the anatomy of the missing region and planning the type of clinical repair technique to be used. In addition, this methodology provides a more regular surface of the reconstructed mandible for analysis, and the use of digital image makes the data further suitable for more computational analysis. Furthermore, a regular surface of the reconstructed mandible can also help in providing better analysis for deciding the control of vector in processes like TDO.

The approach can be extended from pixels to voxels that is the application of the methodology presented here from two-dimensional to three-dimensional reconstruction. As mandible is a dynamic bone, the anatomy keeps changing continuously with age. Also for male and female, the anatomy differs slightly. So we need to form a database of the template mandible for different age groups. Although an adult mandible can be considered as an ideal template that will give very close results on reconstruction, but the same template will not work for a child, as for children the morphological changes in mandible with growth are very fast. Further evaluation of the study with more clinical data, as certain cases of post tumour resection surgery can lead to varied type of defects of the mandibular structure.

With the methodology presented in this work, the reconstruction of the different types of mandibular defects as given in literature, was performed successfully on the image of the mandible. Also the implementation of the methodology for reconstruction and width determination was successfully validated by performing the reconstruction by this methodology of the mandible that was imaged to carry out the validation. Future work has also been indicated.

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