

MANDIBLE PARAMETERIZATION USING A REFERENCE LINE

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Abstract: Using fibula flap for mandible reconstruction becomes a common method. Pre-surgical planning always assumes a known removal portion of mandible to plan the cutting of fibula. Researchers have developed jig or mechanism to assist doctors in measuring and guiding cutting locations of the mandible. However, the true locations of mandible removal are never known. To ease the problem, standard mandible parameters are required to locate the removal area. This paper aims to construct a reference line for parameterizing the mandible. The reference line can be divided into four portions that are coincident with the anatomical features areas of the mandible: Symphysis, Body, Angle, and Ramus. Each portion is then re-sampled into 10-15 sections, and these sections faithfully represent the mandible shape. Thus, all mandibles are re-defined by these 101 sections. Using these mandible parameters, the removal area is recorded by numerical addressable locations to compute the fibula cut, and the mandible and fibula can be aligned according to the parameters for planning the reconstruction.

1 INTRODUCTION

Fibula flap is commonly used in mandibular reconstruction because it has enough length for large-defected reconstruction (Ferri, J., 1997). However, there is no standard procedure for such osteotomy since the shapes between fibula and mandible are quite different. Doctors rely on their own experience to decide a cutting strategy, and this should be performed at the scene. Once the fibula being cut into pieces, it is impossible to redo. For releasing the doctors' pressure and for aesthetic purpose, computer-aided surgical planning are employed recently; most of them used a stereo model (Cohen, 2009; Hallermann, 2006; Yeung, 2007), which is created based on tomography data so that doctors can simulate the reconstruction. However, the true removal locations of mandible defected portion are still unable to know. Besides, the alignment of fibula to the mandible for cutting is performed manually, probably simulated by virtual CAD environment for surgical planning. The cutting planning may be useless if the discrepancy between the true cut and the prediction is large. Some researchers provided mechanisms (Strackee, 2004)

or paper models (Wang, 2009) to record dimensions of the defect section to assist the osteotomy. However, those approaches require assistantship from technicians. The costing and time-consuming processes are tedious and laborious that cannot be automated in computer environment.

Until now, all of pre-surgical planning methods eventually required manual measurement using jig or paper models of mandible cut. Although some researches provided successful examples of rehabilitating defected mandible that were assisted by CAD software (Yoo, 2011; Zachow, 2005), none of them gave a complete solution of mandible osteotomy. For the reason, this study aim to provide a guide for addressing and registering the mandible cutting locations in a computer assisted mandible reconstruction planning. This approach is based on numerical method of mandible feature extraction.

In order to make a standard yardstick, it is necessary to parameterize mandible according to its shape characteristic. In this paper, STL models of mandible are used as an initial data. STL is a popular file format used in CAD software. Most of the CT scanned data can be easily converted into a STL format via commercial available software packages.

However, finding 3-dimensional features of mandible is difficult because of irregular and complicated mesh surface.

In this research, we encoded the 3D mandible STL file into 2D image format with two different view angles and search their medial axes; by integrating the information from the two medial axes, a reference line that represents the profile of the mandible in 3-D space is constructed. Then the bending sections are searched from the reference line. The mandible is then segmented into four portions. Each portion is sliced into several sections. After parameterization, the re-sampled mandible model has standard format that consists 101 sections distributed along the reference line. Each section consists 40 structure points, with first 20 points located in the lingua side and the last 20 points located at the buccal side.

2 REFERENCE LINE CONSTRUCTION

An ideal reference line for mandible should follow three criteria. First, it must be inside a mandible that is similar to a medial-axis. Second, it reflects the shape of the mandible. Finally, it should be smooth enough for parameterization along its shape. The reference line distinguishes from a medial-axis in that, due to rough STL digitization, the medial axis may not be continuous to take derivatives.

2.1 The Best Symmetrical Plane

Since the mandible STL models do not come in at the same coordinate system, it is necessary to find a conformable coordinate system to describe them. Since the mandible is symmetrical in shape, it is nature to find its symmetry plane first. Then a better coordinate system can be constructed, and the mandible can be re-oriented to the coordinate system for subsequent processes. This step is fulfilled by calculating its tensor of moment of inertia. From the major axes of the inertia, the symmetric plane is found and the shape of mandible can be observed in a good view, as shown in Fig. 1.

2.2 Two-dimensional Medial-axis

The vertexes of the mandible STL model are extracted as 3D points which are then encoded into 2D images by projecting the points onto its principle planes, the y-z plane (front view) and the x-y plane (top view) with a proper scale factor, as shown in

Fig. 2. Image processing technique is applied to find the medial-axis in each image. The two 2D medial axes can be obtained by a simple contour thinning process. The medial-axes retain the profile and shape of the mandible in the two principle planes (Fig. 3).

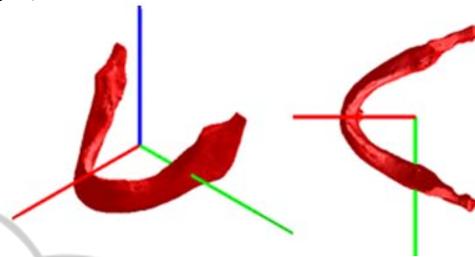


Figure 1: Result of the best plane searching.



Figure 2: Mandible images. (L) Front view (R) Top view.



Figure 3: Medial-axis. (L) Front view (R) Top view.

2.3 Reference Line

Because a medial-axis contains two-dimensional information, two medial axes in orthogonal view preserve the 3D coordinates of the medial-axis. Therefore, a 3D curve that passes through the points of medial-axis can be constructed according to a corresponding coordinate of both medial-axes. Fig. 4 shows such a 3D curve; it is a primary reference line. Obviously, the primary reference line is very rough and discontinuous caused by the image resolution and digitization. In order to make a smooth reference line, we reconstruct the 3D curve by fitting it a B-spline function so that it is smooth anywhere, as shown in Fig. 5.

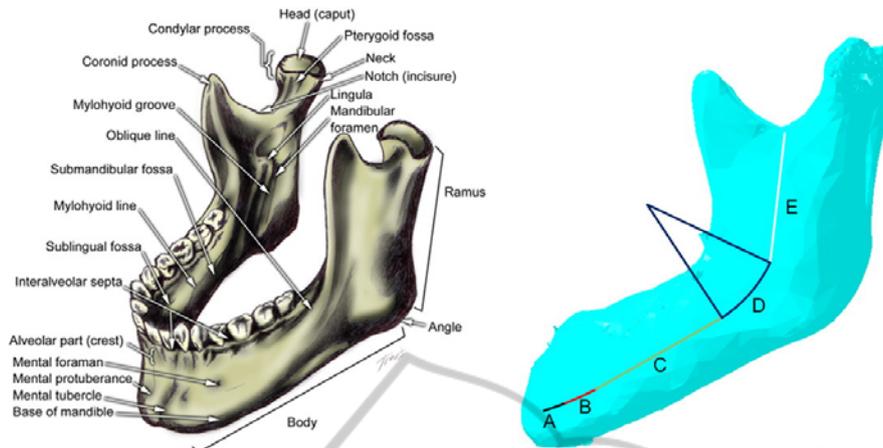


Figure 6: (Left) Mandible anatomy, (Right) Reference line segmentation. The left figure is from <http://withealth.net/en/facial-bone-anatomy>.

3 PARAMETERIZATION

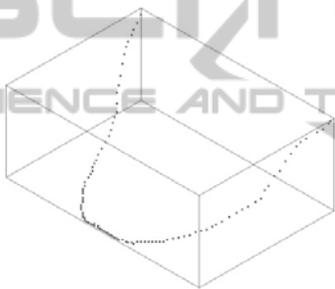


Figure 4: A primary reference line.

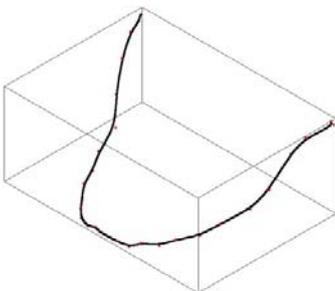


Figure 5: Reference line (B-spline).

A B-spline curve of p^{th} order is defined as:

$$C(u) = \sum_{i=0}^n N_{i,p}(u) P_i \quad 0 \leq u \leq 1 \quad (1)$$

$$N_{i,p}(u) = \frac{u - u_i}{u_{i+p} - u_i} N_{i,p-1}(u) + \frac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} N_{i+1,p-1}(u) \quad (2)$$

$$N_{i,0}(u) = \begin{cases} 1 & u_i \leq u < u_{i+1} \\ 0 & \text{otherwise} \end{cases}$$

Where P_i are control points, and $N_{i,p}(u)$ is the basic function of the B-Spline. The further derivation is described in (Tsai, 2011).

According to the anatomical feature of the mandible, the reference line can be simplified into arc and straight-line portions for the left and right halves (Fig. 7). We search for the bending portions of the reference line using the 3D bending value that extended from 2D (Wang, 1995), the 3D bending value is defined by the following equations:

$$B_p(i) = |X_{fi} + X_{bi}| + |Y_{fi} + Y_{bi}| + |Z_{fi} + Z_{bi}| \quad (3)$$

$$\begin{aligned} X_{fi} &= x_{i+k} - x_i \\ Y_{fi} &= y_{i+k} - y_i \\ Z_{fi} &= z_{i+k} - z_i \\ X_{bi} &= x_{i-k} - x_i \\ Y_{bi} &= y_{i-k} - y_i \\ Z_{bi} &= z_{i-k} - z_i \end{aligned} \quad (4)$$

Where k is a step length indicates the number of point forward and backward. Fig. 7 illustrates a case of $k = 4$.

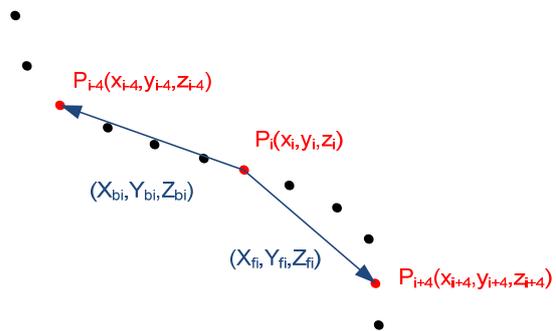


Figure 7: Bending value of P_i with k equal to 4.

According to the bending values, high and low curvature portions of the B-Spline curve can be

distinguished by an appropriate threshold. We then generate arc segments to replace the high curvature portions, and straight-line segments to replace the low curvature portions of the B-Spline curve. The boundary condition between the arc and the straight-line segments is continuous up to the first derivative, i.e. they have the same slope. It is interested to discover the segments are coincident to the “Symphysis, Body, Angle, and Ramus” defined by the anatomy features.

Then, non-dimensional parameters are specified to each segment, and each segment is evenly divided into 10 to 15 nodes according to the length. The parameterization begins from the symmetric node, then Symphysis, Body, Angle, and stop at Ramus. For each left and right side, the Symphysis has ten nodes, Body has 15 nodes, Angle has 10 nodes, and Ramus has 15 nodes. Total of 101 nodes are specified. Every node is given a non-dimensional parameter (NDP). Each NDP contains two characters and a number. The first letter is extracted from the first character of the name of this mandible portion. The second letter specifies the left or right half of the section located. The last digit represents the order of node in this segment (Fig. 8). For example, SL3 means the third node in the left side of Symphysis portion. Tables 1 and 2 list the left and right portions of the NDP code, respectively. Besides, the data structure of each node contains the position (x, y, z) of the node on the reference line of the mandible and the normal vector (I_x, I_y, I_z) of the sectional plane that passing through the node.

Table 1: The NDP codes (left half).

Mandible portion	Left Symphysis		Left Body	Left Angle	Left Ramus
Line segment	A	B	C	D	E
Number of nodes	5+(1)	5	15	10	15
NDP	SL0-5	SL6-10	BL1-15	AL1-10	RL1-15

Table 2: The NDP codes (right half).

Mandible portion	Right Symphysis		Right Body	Right Angle	Right Ramus
Line segment	A	B	C	D	E
Number of nodes	5+(1)	5	15	10	15
NDP	SR0-5	SR6-10	BR1-15	AR1-10	RR1-15

3.1 Sectional Contour of Mandible

The nodes on the reference line preserve the profile of mandible but they alone cannot re-generate the

whole 3D mandible shape. Sectional contour at each node is also required for reconstructing the mandible model. In order to reduce the number of the data point, we just recode the intersection points between the original mandible triangular mesh and the 101 sectional planes. The normal vector of each plane is defined by the direction of the straight-line segments or the tangent of the arc portions. The resultant 101 sectional contours are shown in Fig. 9.

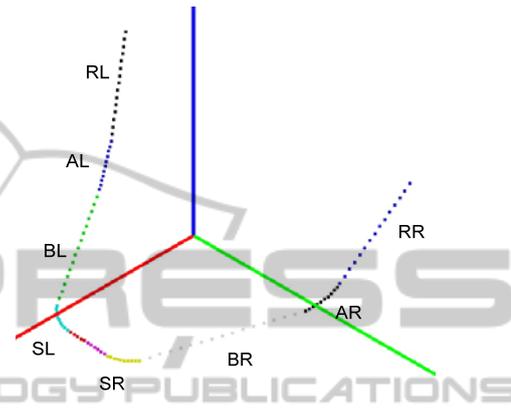


Figure 8: 101 nodes with codes.

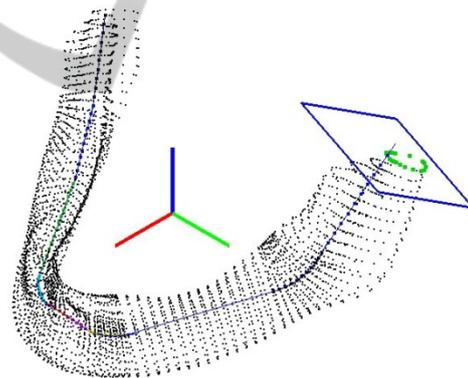


Figure 9: 101 sectional contours of the mandible.

3.2 Structure Points

However, the number of contour point in a section is not the same due to the original meshes of the mandible STL models are not generated in the same density. A normalized method is to re-sample the contour points with equal spanning angle from the node to the perimeter. The re-sampled contour points are called the structure points to preserve the mandible cross-sectional structure. For the contour points in each section, the top and bottom crest points are found first. Then 40 structure points are re-sampled from the contour points; twenty are located in the buccal side, and another twenty are in

the lingua side. Fig. 10 illustrates the definition of the structure points. The lowest point is set as the first point (P_0), and the top crest point is set as the twentieth (P_{20}); the rest of points are generated by interpolation. Based on the definition, the second to the nineteenth point are located on the lingua (inner) side of the mandible, and the twenty-first to the thirty-ninth points are located on the buccal (outer) side.

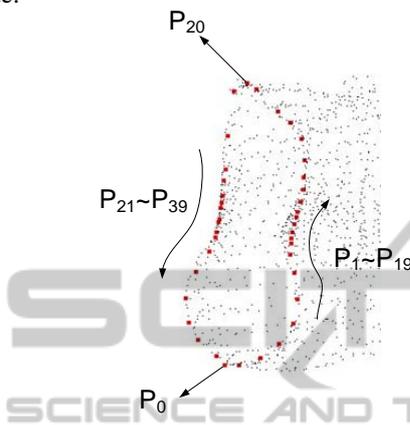


Figure 10: Definition of structure points of a section.

4 RESULT AND APPLICATION

The two mandible STL files in this paper were provided by E-DA hospital (Kaohsiung, Taiwan); it originally contains 44062 and 138564 polygons with 21981 and 68962 vertices, respectively. After parameterization, they all reduced to a standardized 4400 structure points. Triangular meshes can be easily built to reconstruct the mandible STL models.

4.1 Comparison

To evaluate the accuracy of reconstructed mandible model, the differences between the original mandible STL and the newly re-built one were measured. Figure 11 shows a view that the two models are overlapped. The maximum discrepancy between the two models is measured about 0.2 mm, which is precise enough for surgical planning and locating the cutting area for reconstruction purpose. More cases are going to be re-built to verify the algorithm by checking the geometrical integrity and the accuracy of the new mandible models.



Figure 11: Comparison of the original model (in red), and the reconstructed one (in blue).

4.2 Mandible Reconstruction Parameters

For the application of mandible parameterization, we have also developed a user interface to cut the mandible three-dimensionally according to the NDP. Users can move a cutting plane along the reference line, and rotate the plane about two axes defined by the local coordinate of the line to range the defected portion. There are three reconstruction parameters for recording a cutting plane, which are the NDP code of the section on the reference line, and two rotation angles α and β . The rotation angles are, respectively, about the normal and bi-normal vectors of the local coordinate system along the reference line. Fig. 12 illustrates a cutting process using NDP as a guide. Of course, a real cutting guider can be molded according to the NDP code using rapid-prototyping technology.

To plan for the fibula cut, parameterization of fibula based on the same strategy is also necessary. It is easy to do so since the fibula is simply a cylindrical shape. Once the orientation of fibula flap is determined, then align the fibula cross section with that of mandible can be done by using the NDP code. The surgical planning can be accomplished in computer by “placing” the fibula STL model onto the mandible reference line and cutting the fibula into segments. The length of fibula segment can be determined by setting a tolerance between the bended contour of the reference line and the corresponding straight-line contour of the fibula. Moreover, the fibula flap can be placed in a desired orientation on the mandible since the number of structure point indicates the top, lingua, bottom, and buccal side. In all, this study established an infrastructure for the computer assisted mandible reconstruction using fibula flap. Without a standard

parameterization, there would be no information for the removal locations of the mandible, and fibula bone would have no reference to align with the mandible for cutting into segments.

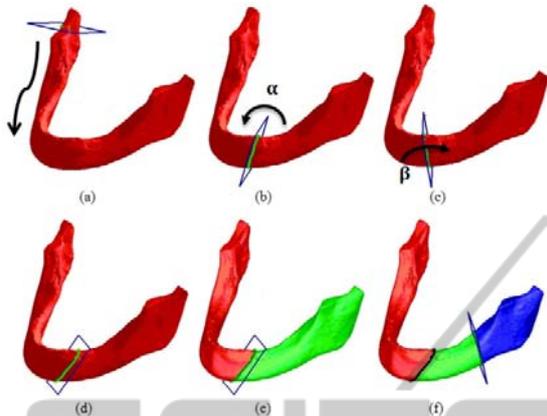


Figure 12: Process of cutting a mandible. (a) Select cutting position. (b) Rotate α degree about x-axis. (c) Rotate β degree about y-axis. (d) Set up the first cutting plane. (e) Result of the first cut. (f) Result of the second cut.

5 CONCLUSIONS

This paper postulates an idea and provides an approach of mandible parameterization using a reference line. The reference line represents the profile of mandible. The reference line is divided into four portions that represent the Symphysis, Body, Angle, and Ramus. The new standardized mandible model has 101 nodes that register as the NDP code. Each section passing through the node contains 40 contour points. These sectional structure points can faithfully regenerate the true shape of mandible. After parameterization, the removal nidus portion of the mandible is indicated by the NDP code and the defected portion can be reconstructed by using the parameters as a guide. Besides, the order of structure point also indicates the orientation of the mandible cross-sectional direction, especially the lingua and buccal sides, which facilitates the placement of the fibula flap on the right orientation of the mandible. The parameterization makes the mandible reconstruction by numerical computation possible. It is essential for surgical planning in a CAD system, which is our future work to be done.

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