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Volumetric Surgical Planning System for Fibular Transfer in Mandibular Reconstruction

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Abstract— **This presentation introduces a new software design for virtual preoperative planning for free fibular transfer in mandibular reconstructive surgery. Direct volume resection and manipulation of superimposed fibular segments allow interactive editing of the surgical plan without the need for a surface modeling process. We also introduce three shape indicators: volume ratio, contour error and maximum projection for evaluating the reconstruction plan from geometrical aspects. The indicators significantly quantify the difference between 2-segment and 3-segment cases, and suggest optimization of preoperative planning while satisfying appropriate placement margins for fibular segments.**

I. INTRODUCTION

Microvascular free fibular transfer has become a common procedure in mandibular reconstruction [1]. In surgery, fibular segments are transplanted into the mandibular defect while considering the curved shape and the mastication functions of the mandible. The goal of the surgery is to achieve stable and precise mandibular reconstruction and structural, esthetic, functional recovery of the patient's native face. Although clinical efforts have been made to improve the accuracy of reconstruction [2], fibular osteotomy and mandible reconstruction remain a challenge and are still largely dependent on the surgeon's experience, intraoperative decisions and technical skills.

Virtual surgical planning has recently been focused on as a means of supporting preoperative design of the reconstructive procedure using patient's CT volume data [3, 4, 5]. The advantage of computer-aided planning is it allows rapid design of a patient-specific surgical procedure, quantitative evaluation for optimization and visualization of three-dimensional structures that can be intuitively shared between surgeons, technicians and other medical staffs [6, 7]. Using software, the surgeons or technical staffs can simulate mandible reconstruction incorporating three-dimensional fibular shape models. However, the current designs of virtual surgical planning are mostly based on manual operation and require a trial-and-error process to refine the reconstruction plan [4, 5]. Since surface representation is commonly used for visualizing bone structures, a re-meshing process is frequently required for editing their shape. This factor can cause additional loads and time-consuming modeling time to achieve the optimal surgical plan. As far as we surveyed, there is still no report on a practical system or software design that is available for direct use by the surgeons in fibular transfer planning.

This presentation proposes a volumetric surgical planning system that supports preoperative planning of free fibular transfer in mandibular reconstruction. Unlike previous planning software and systems, we entirely utilize volumetric representation for the bone structures. This enables us to avoid the mesh generation process frequently used in shape editing. In the system we have developed, fibular segments are fused with mandibular structures and volumetrically rendered based on updates to the user's the surgical plan. Also, in order to approach optimization of the preoperative planning, we newly introduce shape indicators to quantify planned mandible reconstruction. The proposed software and indicators were tested by applying 9 patient's CT data. This paper shows some planning examples and discusses the computation results of the shape indicators.

II. METHODS

In the proposed preoperative planning system, virtual resection is first performed to define appropriate margins for removal of cancer or for reconstruction of mandibular defects. The resection area is determined using the boundary surfaces and semi-transparently visualized through volume rendering (Figure 1a). A set of three-dimensional vectors (**P**, **N**) are the controllable parameters for defining the virtual plane *S*. $\mathbf{P}_0$ and $\mathbf{P}_2$ also represent connection points between the patient's native mandible and the fibular segments as well as define the boundary. Similarly, $\mathbf{P}_1$ is used as a connection point between the two fibular segments. These connection points are directly placed on the surface of the volumetrically rendered native mandibular. When the user indicates a pixel on the rendered image, the corresponding voxel located on the mandibular surface is estimated in the volumetric space by accumulating alpha values along the line of sight from the camera. This process is similar to the ray casting protocol [8] commonly used for the volume rendering scheme. After placing the virtual planes, the user can translate and rotate the planes to change the resection area.

Next, fibular segments are also defined by a set of virtual planes placed on the fibular volume data. Figure 1b shows two fibular segments defined by four planes S_a, …S_d. A three segment case is similarly defined using six virtual planes. Here, each plane placed on the fibula is mapped to the

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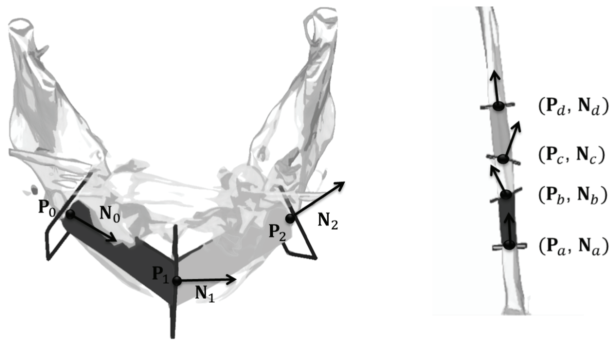


Figure 1. Geometrical representation in the preoperative planning system, (a) volume visualization of mandibular reconstruction with fibular segments and (b) colored fibular segments used for reconstruction

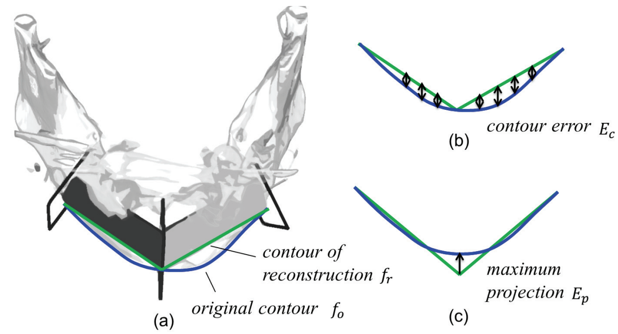


Figure 2. Definition of the contour error and the maximum projection as shape indicators in the preoperative planning

corresponding plane S_k (k = 0,1,..) assigned by the user to the mandibular images. For example, the virtual plane S_a is described by a three-dimensional point $\mathbf{P}_a$ constrained on the central line of the fibula and a normal vector $\mathbf{N}_a$. ($\mathbf{P}_a$, $\mathbf{N}_a$) and ($\mathbf{P}_b$, $\mathbf{N}_b$) are mapped to ($\mathbf{P}_0$, $\mathbf{N}_0$) and ($\mathbf{P}_1$, $\mathbf{N}_1$) respectively while satisfying the equation (1) and (2).

$$\left|\mathbf{P}_1 - \mathbf{P}_0\right| = \left|\mathbf{P}_b - \mathbf{P}_a\right| \tag{1}$$

$$\mathbf{N}_0 \cdot \mathbf{N}_1 = \mathbf{N}_a \cdot \mathbf{N}_b \tag{2}$$

Based on this mapping and constraints, the fibular segments are superimposed onto the mandibular volume. The estimated fibular segments are simultaneously visualized by coloring the corresponding area of the fibular volume. In order to refine the reconstruction plan, the traditional design of the planning software requires trial-and-error manual operation relying on the user's clinical experience and anatomical knowledge. Since three-dimensional operation is necessary to ascertain the optimal reconstruction plan, manual operation may cause placement errors due to lack of three-dimensional information such as occlusion. For these issues, the developed system implements quantitative indicators to evaluate the current planning state. In this paper, as a first approach to quantification, we introduce three shape indicators: *volume ratio*, *contour error* and *maximum projection*.

A. Volume ratio

The reconstructed mandible should have a sufficient volume to maintain its postoperative mastication function and physical strength [9] as a part of the facial bone. Especially, we focus on the volume ratio that quantifies the amount of filling for the resection regions with the fibular segments. The indicator E_v on the volume ratio is described as Equation (3).

$$E_v = \frac{\sum V_{fib}}{V_{cut}} \tag{3}$$

where V_{cut} is the volume of the resection area, and $\sum V_{fib}$ is the sum of the volume of the fibular segments placed in the resection area. This indicator is affected from fibular osteotomy and placement of the fibular segments. For example, if thicker parts are selected from the fibular volume, the indicator shows higher values.

B. Contour error

The postoperative appearance of the patient's face is affected by the contour of the reconstructed mandible [4, 10]. In order to quantify the contour on the given surgical plan, we define the contour error E_c using the average distance between the contour of the placed fibular segments f_r and the original contour f_0 of the patient's mandible. This indicator is defined using Equation (4).

$$E_c = \frac{1}{l}\int_C |f_r - f_o| dr \tag{4}$$

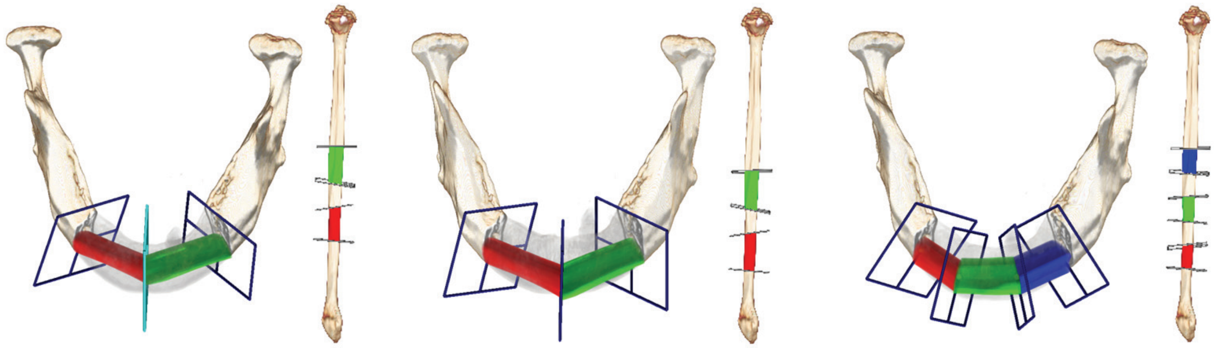
where l is the total length of the patient's native contour in the given resection area. In the computation, the xyz-coordinates to mandibular images are first placed based on the occlusion plane of the patient's mandible. The normal vector of the occlusion plane is set as the z-axis as in Figure 2a. As shown in Figure 2b, we compute $\left|f_r - f_o\right|$ as the Euclid distance between discrete sample points on the two contours. The sample points are obtained by scanning two surface positions of the mandible and of the fibular segment in the y- and z-directions from the discrete points composing the centerline of the fibula.

C. Maximum projection

The two shape indicators introduced above do not evaluate the amount of the fibular segments placed outside of the resection area (see Figure 2c). Although the protruding part of the bone could be additionally resected during the surgery, the available margin for resection is restricted within the thickness of the cortex. Therefore, we employ maximum projection E_p as a third indicator to filter inadequate placement of the fibular segments. E_p is obtained based on Equation (5).

$$E_p = \max(|f_r - f_o|) \quad \text{subject to } f_r > f_o \tag{5}$$

In summary, the concrete preoperative planning procedure using the developed software is as follows.



(a) (b) (c)

Figure 3. Virtual planning examples and estimated fibular segments for mandibular reconstruction. (a) initial placement of the fibular segments, (b) the reproduced surgical plan in 2-segment case and (c) the surgical plan in 3-segment case

STEP 1 Virtual resection
The resection area is first determined by placing the boundary surface *S*. When the user clicks a part of the rendered mandibular image, the system estimates the surface position on the mandible and generates the control points $\mathbf{P}_i$. These points also represent the connection points between the patient's native mandible and each of the fibular segments. The number of connection points is three in the 2-segment case and four in the 3-segment case. The normal vector $\mathbf{N}_i$ is initiated based on the placed control points.

STEP 2 Fibular transfer simulation
After setting virtual resection and the number of segments to be used for fibular transfer, the controllable virtual planes S_k ($k = 0,1,..$) are placed on the rendered mandibular image. The user interactively manipulates the placed virtual planes (e.g. rotation and translation) to refine the surgical plan. When a virtual plane is manipulated, the corresponding planes placed on the fibula are also updated simultaneously to reflect the changes. Finally, all fibular segments including their shape and their length are simulated based on the planned fibular transfer.

STEP 3 Stereolithographic model generation
A 3D virtual model with an annotated surgical plan is constructed for stereolithographic model production. The created model is stored as a STL format and can be directly applied to a 3D printer.

III. Results

The proposed preoperative planning system was tested by applying CT datasets of measurements from 9 patients with oral cancer. We implemented the overall algorithms using C++, GLSL and CUDA. A standard PC (CPU: Intel Corei7 2.93 GHz, Memory: 16GB) with a general-purpose graphic card (nVidia GeForce GTX580) was used for the test. The CT slice images were first re-sampled as volume data with 256^3 voxels. The mandible part was extracted from the head CT data, and the fibula was extracted from the foot CT data. This segmentation step was completed in 2-3 minutes for each case based on region growing based ROI selection and manual removal of voxels with a 3D cutting tool [11].

In the experiment, oral surgeons and dental technicians reproduced the past surgical plans retrospectively without relying on the proposed shape indicators. Two types of mandibular reconstruction using 2 or 3 fibular segments were simulated. Figure 3 demonstrates the reconstruction examples and the estimated fibular segments. Thus, fibular transfer simulation results are volumetrically rendered by superimposing fibular segments onto the resection area of the mandible. Figure 3a shows initial the placement of fibular segments. The central virtual plane colored in light blue was selected and operated on through translation and rotation. Figure 3b is the surgical plan adjusted through manual operation by the user. The angle of two fibular segments was updated through translation of the connection point. The parts of the fibula selected for fibular segments were also changed. Figure 3c shows the 3-segment case interactively configured by the oral surgeon. The two connection points between each of the fibular segments were translated to fit them to the contour of the patient's mandible. In order to maintain postoperative of the reconstructed mandible, the reconstruction plan is modified under the condition that each fibular segment has a sufficient length.

After setting the surgical plan for all cases, the experimenter computed the shape indicators. The average of the contour error was 2.78*mm* in 2-segment case and 1.64*mm* in 3-segment case. This result suggests the 3-segment case has a greater possibility for achieving better reconstruction of the mandibular contour. This result is also more natural from the mathematical point of view (i.e. linear interpolation of the facial curve)

Although the 3-segment case can provide a good score in our experiments, the 2-segment case is still a choice for actual surgery because of the intraoperative burden for patients in the 3-segment case. We have examined the maximum projection E_p in the 2-segment case to investigate the available margins of the placement. The average E_p on the surgical plan assigned by the oral surgeon was 1.93*mm*. This value is sufficiently low because the minimum thickness of the cortex is estimated to be 3-4*mm* from patient's CT images.

Using 1.93*mm* for the threshold of the placement margin, we tried to explore the optimal reconstruction that shows the best contour error. This search was conducted by updating the connection point $\mathbf{P}_1$ from -3 to +3 voxels in *xyz*-direction. 343 patterns of the placement were examined, and the optimal position with minimum contour error was determined. We re-computed the indicators on the optimized 2-segment case and found the average of the contour error was improved to 2.27*mm*. Thus, the shape indicators quantify the surgical plan from geometrical aspects and suggest the applicability for optimization of the mandibular reconstruction.

IV. CONCLUSION

This paper presented a new software design for the preoperative virtual planning for free fibular transfer in mandibular reconstructive surgery. Direct volume manipulation and visualization of multiple objects allow interactive editing of the surgical plan including virtual resection without the need for a surface modeling process. We also introduced three shape indicators: the volume ratio, the contour error and the maximum projection for evaluating the surgical plan from geometrical aspects. The proposed indicators quantify the difference between 2-segment and 3-segment cases and suggest optimization of preoperative planning while satisfying appropriate placement margins of fibular segments. Our future work is to approach further quantification for physical evaluation of the reconstruction plan and automation of the preoperative planning protocol.

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REFERENCES

[1] O. Tepper, D. Hirsch, J. Levine, E. Garfein, "The New Age of Three-Dimensional Virtual Surgical Planning in Reconstructive Plastic Surgery, Plast Reconstr Surg, vol. 130, no. 1, pp. 192-194, 2012.

[2] Y. Yamanaka, H. Yajima, T. Kirita, H. Shimomura, S. Tamaki, K. Aoki, N. Yamakawa, Y. Imai, "Mandibular Reconstruction with Vascularised Fibular Osteocutaneous Flaps using Prefabricated Stereolithographic Mandibular Model", Journal of Plastic, Reconstructive & Aesthetic Surgery, Vol.63, pp. 1751-1753, 2010.

[3] J. Sink, D. Hamlar, D. Kademani, S. S. Khariwala, "Computer-Aided Stereolithography for Presurgical Planning in Fibula Free Tissue Reconstruction of the Mandible", J Reconstr Microsurg, vol. 28, no. 6, pp. 395-404, 2012.

[4] A. K. Antony, W. F. Chen, A. Kolokythas, K. A. Weimer, M. N. Cohen, "Use of Virtual Surgery and Stereolithography-guided Osteotomy for Mandibular Reconstruction with the Free Fibula", Plast Reconstr Surg, vol. 128, no. 5, pp. 1080-1084, 2011.

[5] Y. Shen, J. Sun, J. Li, T. Ji, M. Li, W. Huang, M. Hu, "Using Computer Simulation and Stereomodel for Accurate Mandibular Reconstruction with Vascularized Iliac Crest Flap", Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology, vol. 114, no. 2, pp. 175-182, 2012.

[6] S. M. Roser, S. Ramachandra, H. Blair et al., "The Accuracy of Virtual Surgical Planning in Free Fibula Mandibular Reconstruction: Comparison of Planned and Final results", J Oral Maxillofac Surg. vol. 68, pp. 2824–2832, 2010.

[7] X. Chen, J. Yuan, C. Wang, Y. Huang, L. Kang, "Modular Preoperative Planning Software for Computer-aided Oral Implantology and the Application of a Novel Stereolithographic Template: a Pilot Study", Clin Implant Dent Relat Res., vol. 12, no. 3, pp.181-193, 2010.

[8] M. Nakao, K. W. C. Hung, S. Yano, K. Yoshimura and K. Minato, "Adaptive Proxy Geometry for Direct Volume Manipulation", IEEE Pacific Visualization, pp.161-178, 2010.

[9] A. Bottino, M. D. Simone, A. Laurentini, C. Sforza, "A New 3D Tool for Planning Plastic Surgery", IEEE Trans Biomed Eng., vol. 59, no. 12, pp. 3439-49, 2012.

[10] Kimsal J, Baack B, Candelaria L, Khraishi T, Lovald S. Biomechanical analysis of mandibular angle fractures. J Oral Maxillofac Surg, 69(12), pp. 1798-1806, 2011.

[11] K. Imanishi, M. Nakao, M. Kioka, M. Mori, M. Yoshida, T. Takahashi and K. Minato, "Interactive Bone Drilling using a 2D Pointing Device to Support Microendoscopic Discectomy Planning", International Journal of Computer Assisted Radiology and Surgery, Vol. 5, No. 5, pp. 461-469, 2010.