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Computer based framework for cranio-maxillofacial surgery planning

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Abstract

Nowadays the process of surgical planning is a crucial point of every operation in the craniofacial region. In this work we focus on the planning of graft reconstructive surgery for autologous osseous grafts. The planning method consists of two stages. The non-automatic graft design step is followed by a fully automatic procedure to find the best harvesting site in the predefined donor region. The main idea of the proposed method is based on the registration paradigm. The optimal donor site is identified by performing an optimization of the surface based similarity measure between the donor region and the designed graft template. An efficient optimization method based on the Levenberg-Marquardt algorithm has been implemented.

1. Introduction

Craniofacial surgery is a highly complex reconstructive surgery providing comprehensive surgical treatment for facial deformities consequent to trauma, cancer removal and congenital malformations. In this paper we focus on facial restoration problems with emphasis on reconstructive surgery of the mandible.

The mainstay of mandibular reconstruction rests with the replacement of missing mandibular segment by autogenous bone grafts. Autogenous grafts (called also autologous) are osseous grafts taken from one anatomic site and transplanted to another part of the body in the same individual. To achieve satisfactory incorporation of the autologous graft into the host bone, precise individualized planning and simulation of the surgical intervention is required. Planning techniques have changed markedly over the last decades, particularly with the advent of computed tomography. The volumetric CT datasets enable not only noninvasive exploration of the defected area and the harvesting region

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but also fabrication of patient-specific stereolitography models, which can be used to plan individualized osteotomy procedures. The main drawback of these conventional graft surgery planning methods is the lack of the quantitative quality estimation of the selected donor site for a given template. To overcome this drawback a computer-aided method for semi-automatic selection of the optimal harvesting site has been developed [1]. The main idea of the proposed method is based on the registration paradigm. The optimal donor site in the donor region for a given graft's template can be seen as an optimal alignment of two objects according to some mathematically formulated optimality criteria. The optimality can be defined in many ways. In a number of our previous works [1-2] the novel surgery planning method and its improvements have been presented. In this work we have focused on the mathematical criterion, which utilizes a distance notion defined for two surfaces extracted from the preoperative CT datasets, as well as on the new deterministic optimization method. In the next section we formally define and discuss the main components of the registration framework used in our surgery planning system and after that we present practical applications of the developed tool.

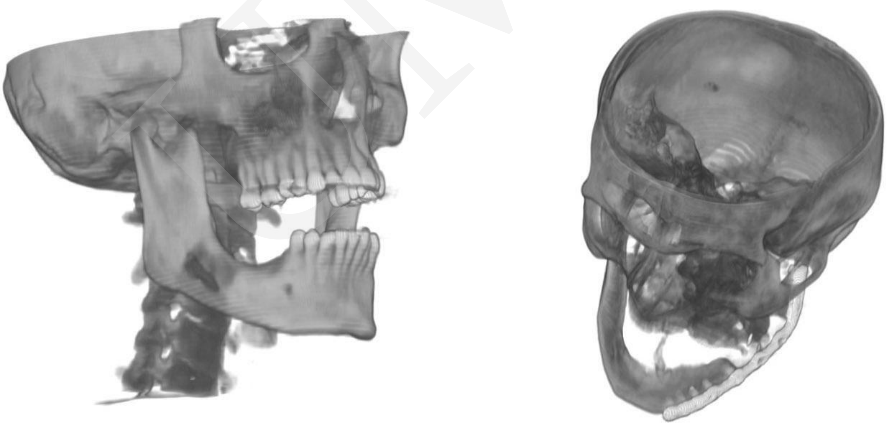

Fig. 1. Volume rendering of a skull with the tumor in the alveoral part of the patient's right hemimandible (left) and the craniofacial area after trauma (right). The defected mandible has been initially stabilized by using a bone plate

2. Methodology

Our computer-aided surgery planning method consists of several stages (see Figure 2). After the acquisition of CT datasets corresponding to both regions of interest a segmentation and triangulation step is performed. The graft's template is defined based on the generated virtual patient-specific anatomical model of the defected site. In the second virtual model the donor region is defined where the surgeon is looking for the optimally aligned bone segment. The non-automatic step of graft design and constraint setting is followed by a fully automatic procedure to find the best-fitting position. We consider two 3D objects: *template* and *donor region* that are extracted from both pre-operative CT datasets. From the mathematical point of view the donor site selection problem can be stated as an optimization problem under certain geometric constraints. We assume that the *template* is geometrically transformed in the matching process to fit the *donor site*.

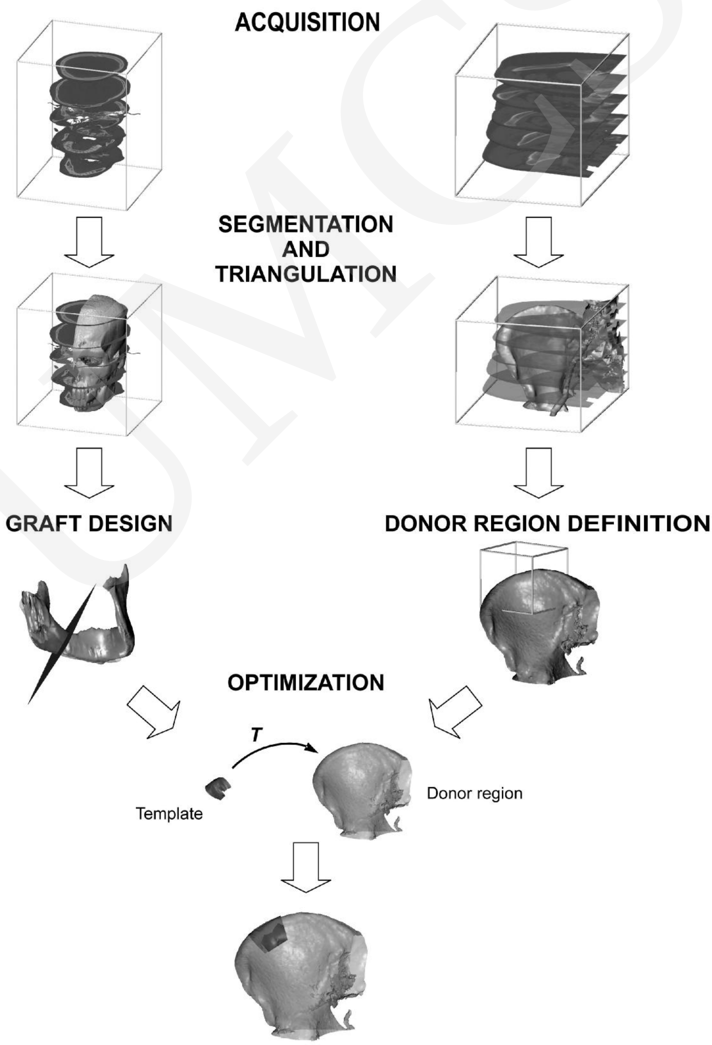

Fig. 2. Data flow in the computer-assisted optimal donor site selection method for autologous osseous grafts

Let $T:\Re^3 \to \Re^3$ be a rigid transformation that transforms a point p from one dataset to another. Let $d(p)$ be the Euclidean distance in $\Re^3$ between any transformed point p and the closest to data point p' and it denotes the length of the vector that is defined by that pair of points $d(p) = \min\|p - p'\|$. For any vector $v = (r_x, r_y, r_z, t_x, t_y, t_z) \in \Re^6$ the surface similarity measure $C(v)$ can be defined as follows:

$$C(v) = \sum_{i=1}^{N} d^2(T_v(p_i)), \tag{1}$$

where $d(T_v(p_i))$, is the distance between the position of the *template* point p after being transformed by T and the closest point of the *donor site* as defined above. N is the number of points defining the extracted *template* surface. Estimation of the optimal transformation vector v_{opt} defining a rigid transformation T_{opt} that minimizes the misregistration measure between the *template* and the *donor site* is the goal of the optimization process. Because the misregistration measures are non-linear functions they can have multiple local minima on the feasible set [1]. Previously, the simulated annealing [3] – a non-deterministic optimization method – has been applied in our system to solve the optimization problem for the applied misregistration measures. The method is very robust and non-susceptible to local minima. But the drawback is, it is very time consuming approach. To overcome this drawback we have decided to use another approach – the deterministic one. The Levenberg-Marquardt method [4] is a standard non-linear least-squares optimization technique working robustly for a wide range of applications. The method requires partial derivatives of the objective function with respect to all parameters. The Levenberg-Marquardt algorithm uses a search direction that is a cross between the Gauss-Newton direction and the steepest descent [4]. This is a powerful iterative algorithm that can be used to minimize many objective functions, for which other algorithms like Newton or the simple steepest descent method do not work satisfactorily. The computation of the distance $d(T_v(p_i))$ during the calculation of the misregistration function (1) is the most time consuming part of the whole optimization stage. This process can be accelerated by computing 3D distance map in the pre-processing phase [5, 6]. The distance transform is an operator that can be applied on the 3D binary surface dataset. Each single voxel in the created distance map is labeled with its distance from the nearest boundary point. There are several different types of the distance transform. Depending on the distance metric used to determine the distance between voxels there are, for instance, Euclidean, chamfer, chessboard, and city-block distance transforms. Euclidean distance computation allows calculation of all three spatial coordinates of a distance vector. These parameters can be used in the optimization process to estimate derivatives of the objective function. In some cases we can reduce the optimization time again by computing the distance map only for a certain region of interest (see the bounding boxes in Figure 4). Thus, this new optimization approach based on the Levenberg-Marquardt algorithm enables, once the pre-processing step has been performed, selection of the optimal donor site in time less than one minute.

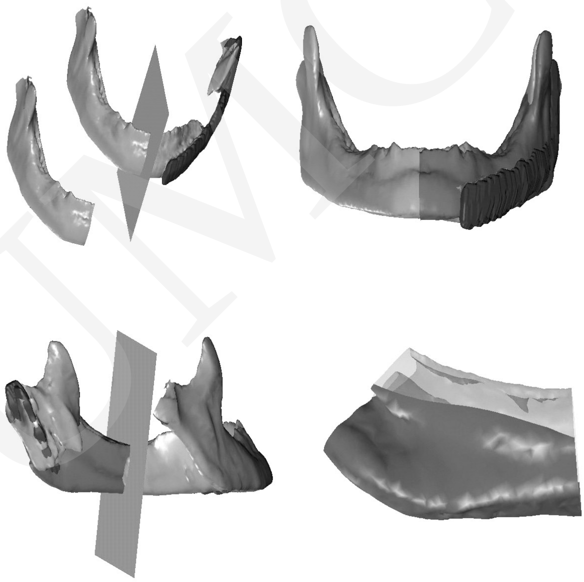

Fig. 3. Graft design using mirror technique for large craniofacial defects. The dark object nearby the right hemimandible is a bone plate rigidly fixing the defected site

3. Results

Our surgery planning system has been written in C++ and uses Qt library [7] for creating the graphical user interface as well as VTK [8] and OpenGL [9] libraries for 3D visualization and real time interaction. Because these libraries are fully cross-platform, the system is operating system independent. The ability to interact with complex medical datasets in 3D space is essential for many medical applications dealing with the volumetric data. It is particularly important for the treatment planning software. In our system the visual exploration of the selected donor site or the defected area can be carried out by a wide range of the implemented visualization techniques. Beside the conventional 2D slice views and surface rendering methods (see Figure 4) the physician can use hardware accelerated real-time volume rendering of the required region of interest (see Figure 1). For the graft design step the system provides segmentation and marking tools, which allow the surgeon to delineate precisely the osteotomy border lines in the template dataset and to define the geometrical constraints in the donor site dataset (see Figure 4). Once the graft design step is completed the system enables the surgeon to generate a set of sub-optimal and optimal donor sites for a given template. All generated solutions can be explored interactively using the visualization tools described above. Our system enables also the virtual reconstruction of the defected site using the virtually harvested graft (from the pelvis virtual model).

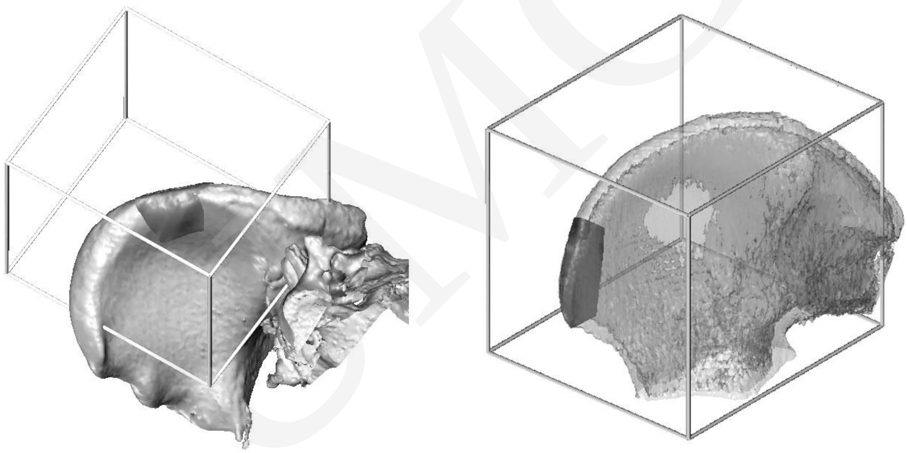

Fig. 4. Pelvis with superposed templates (from the Figures 1-left and 1-right accordingly) positioned at the automatically estimated optimal donor sites

The mandible reconstructed using this option for both cases has been shown in the Figure 6. All CT data have been acquired on the Siemens and Philips scanners with high-resolution protocols. The grafts were taken from the area of the iliac crest. In Figure 1 two craniofacial disorders are shown. Both cases have been classified for the autograft reconstruction and the surgical treatment was performed as a grafting procedure using cortico-cancellous bone grafts harvested from the patient's own iliac crest. The preoperative planning process has been carried out using stereolitography models of the craniofacial region and the pelvis as well as by using our planning system.

In the first case (see Figure 1 left) graft has been designed by using standard cutting planes. For the large bone defect in the second case (see Figure 1 right) the graft design step has been performed using a mirror technique (see Figure 3).

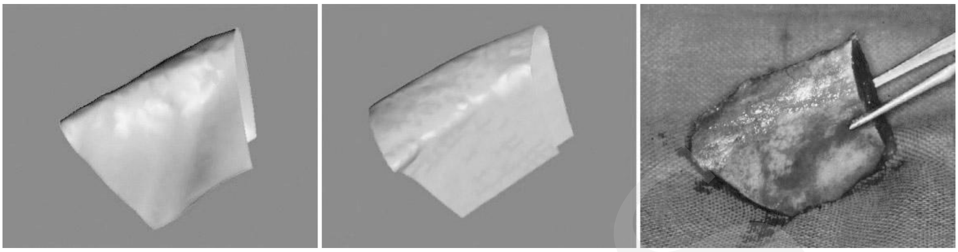

Fig. 5. Different graft instances in the surgery planning and treatment of the Case 1 (see Figure 1-left): graft's template designed for the mandibular reconstruction (left), the graft surface virtually harvested from the identified optimal donor site in the pelvis bone (middle), surgically resected osseous graft from the planned donor site (right)

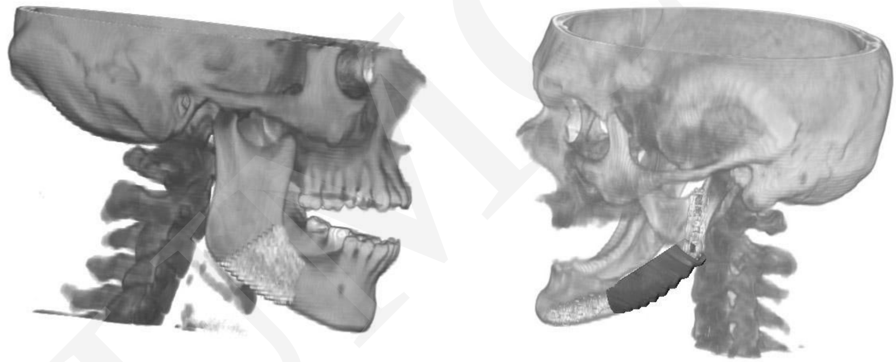

Fig. 6. Virtual reconstruction of the defected site – volume rendering (left - Case 1) and volume & surface rendering (right – Case 2)

In this method the healthy side is duplicated, mirrored and aligned with the pathological side. The required grafts shape is then defined in the symmetrically formed template. The estimated optimal donor sites for both designed graft templates are presented in Figures 4-left and 4-right. The bounding boxes shown in both figures define the feasible region of the optimization step for which the 3D distance map is precalculated. The selected donor sites are optimal according to the mathematical formulation of the problem and they are highly consistent with the harvesting site in the operation theatre. The robustness of our surgery planning system and high compatibility of the planned graft's shape with the shape of the harvested one is presented in the Figure 5. The computation times (performed on PC, Pentium III, 600 MHz, 768 MB) for the Levenberg-Marquardt optimization step in these two cases (see Table 1) illustrate high effectiveness of the presented surgery planning method. Continuous follow-up observations show that there is less loss of transplants, when they are individually designed as well as higher assessment of function, phonetics and esthetics of the final outcome of the treatment. Moreover, in most cases the duration of surgical interventions has been distinctly reduced due to computer-assisted preoperative osteotomy planning.

Table 1. Running times for the Levenberg-Marquardt optimization method (surface similarity measure) in the two planning cases showed in Figures 1-left and 1-right

	Case 1	Case 2
Donor region size	81x108x26	181x185x91
# template points	2589	1677
Preprocessing time	26.5 sec	39.7 sec
Optimization time	14.9 sec	10.1 sec

4. Discussion

We have presented a semi-automatic treatment planning method for selection of optimal harvesting sites for autologous grafts in the craniofacial graft surgery. The proposed method provides an effective tool in the planning of reconstructive bone surgery. It has obvious advantages over the conventional planning methods, like stereolitography models or manual matching of the segmented objects. It allows quantification of the matching quality as well as automation of the selection process. The implemented deterministic optimization method and the object manipulation and visualization tools allow fast estimation of the optimal donor site and effective exploration of the identified harvesting site. The practical tests on the patient datasets show that the optimal donor sites for autologous osseous grafts can be successfully determined using the registration approach. The method is generally applicable for various autologous grafts regardless of its shape and the grafting or donor site. By this approach, not only treatment planning time but also the operation time can be considerably reduced.

5. Acknowledgments

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