computer-aided surgery, osteotomy planning, autologous grafts, transplant design, matching similarity measure, donor site, optimization.

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PATIENT-SPECIFIC GRAFT DESIGN METHOD FOR CRANOFACIAL SURGICAL PLANNING

This paper presents a method for computer assisted selection of optimal donor sites for autologous osseous grafts in the craniofacial surgery. At the initial graft design stage the surgeon defines in the CT data set the shape of the bone segment to be reconstructed and in the donor region CT data set a set of constraints for the optimization task. This non-automatic step is followed by a fully automatic optimization stage, which delivers a set of sub-optimal and optimal donor sites for a given template. Such approach permits the surgeon to find the best site for harvesting the graft and enables an exact anatomical reconstruction of the osseous section.

1. INTRODUCTION

The concept of using autogeneous or allogenous bone to fill an osseous defect has a long history in medicine, but the scientific knowledge that has made modern transplant medicine possible dates primarily from the 19th and 20th centuries. In 1915 F.H. Albee published an influential text on bone graft surgery[1]. Since then, the bone grafting has became more widespread and attention focused not only on its use, but also on its safety and efficacy. Grafting techniques have markedly changed over the last decades in an attempt to provide better correction of the bone defects, enhance stabilization, and increase the rate of bony consolidation. Today it is certainly considered acceptable standard method for many surgical indications. Computed tomography has added a new dimension in this domain. The information acquired by imaging devices allows the physician to produce a detailed and optimized plan of treatment. This work focuses on the planning of grafting procedures for osseous grafts transplanted from one part to another part of the body in the same individual. The problem of graft surgery arises from the need to reconstruct the osseous defects after tumor, trauma, infection or in the treatment of congenital malformations (see Figure 1). The autologous bone transplants can be harvested from different donor sites. Depending on the

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amount and shape of the bone graft required, it can be harvested from the ilium, rib, cranium, scapula, or tibia bone. For reconstruction of the craniofacial region, which is our area of interest, the iliac bone is the most often material of choice because of the anatomical similarity with the recipient region. It is ideal for orbital roof and floor repairs, but above all for mandibular reconstruction. The major problem in the graft surgery is to determine as accurately as possible the donor site where the graft should be dissected from and to define the shape of the desired transplant. In a number of our previous works[2,3] a novel method and its improvements for selection of optimal donor sites for autologous osseus grafts have been presented. In this work we introduce an improved computer-aided surgery planning system which enables efficient segmentation, visualization and manipulation of the virtual patient model prior to operation. By using a deterministic optimization method the physician can significantly accelerate the selection of the optimal donor site.

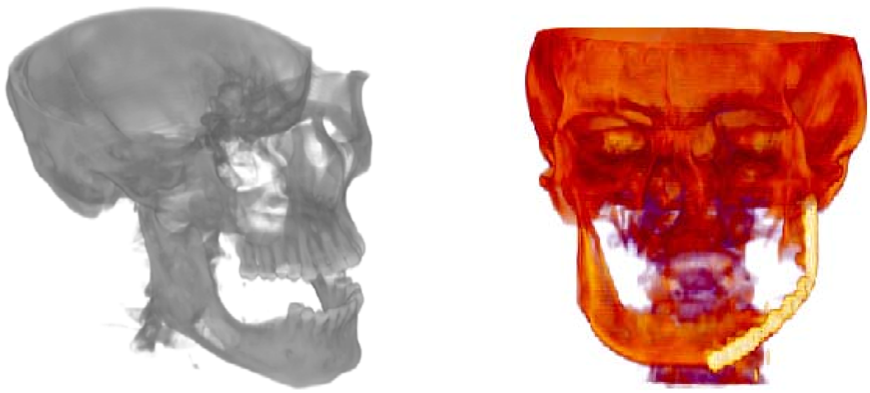

Fig.1. Volume rendering of a skull with the tumor in the alveoral part of the patient's right hemimandible (left) and the craniofacial area after trauma (right).

2. METHODOLOGY

From the medical point of view the osseous graft surgery is an operative technique, where the defected bone is resected, then the designed graft is harvested from the identified donor site and transplanted into the resected section. The reconstructed bone section is then fixed with bone plates and screws, until the healing process is complete. Successful bone graft repair depends on a number of factors. These include (1) close approximation of the shape of the bone section to be reconstructed, (2) supplying of the structural support to the recipient site (3) rigid fixation and (4) minimal lesion of the donor site. To achieve satisfactorily incorporation of the graft into a viable new bony complex, precise planning and simulation of the surgical intervention based on 3D CT studies acquired prior to surgery is required. Inaccurate design and harvesting may lead to loss of the graft. In our continuing work on the computer assisted selection of donor sites for autologous grafts we have developed a method to identify an optimal match between donor region and a given transplant. Let us briefly describe the main idea of the proposed method. More detailed description can be found in our previous publications [2,3].

We consider two pre-operative CT datasets: *template* and *donor site*. The shape of the desired transplant is defined in the *template* dataset and the *donor site* corresponds to the dataset which is acquired from the part of the body where the graft should be dissected from. Let $T:\mathbf{R}^3 \to \mathbf{R}^3$ be a rigid transformation that transforms a point **p** from one dataset to another. The problem of matching a desired transplant with the donor region can be posed as an optimization problem where the objective is to minimize some misregistration measure between the features defined in both datasets:

$$v_{opt} = arg\ min\{\ C(v)\ |\ v \in M\} \tag{1}$$

where C(v) is an objective function and $M \subset \mathbf{R}^6$ is a set of permissible parameter vectors which satisfy some constraints. The goal of the optimization is to find the parameter vector v_{opt} defining a 3D rigid transformation T_{opt} which minimizes the misregistration measure C between the template and the donor site. Several similarity criteria have been tested[3] and the most efficient of them have been chosen for our surgery planning system. These include surface matching[4], normalized mutual information[5] and s-distance measure[3]. Each of the matching functions belongs to different similarity measure classes: surface based metrics, voxel based metrics and cross-metrics, accordingly. It enables the surgeon to select the optimal donor site not only in terms of bone surface correlation but also according to the whole morphological information contained in both datasets.

Our method consists of several stages (see Figure 2). After the acquisition of volumetric CT data and segmentation of two relevant osseous structures, the surgeon indicates interactively the osteotomy border lines in the *template* CT dataset and defines a set of constraints for the optimization task in the *donor site* CT dataset. At the final stage a fully automatic optimization procedure delivers a set of sub-optimal and optimal donor sites for a given template. The graft design step and the improved optimization method are discussed in the next two sections.

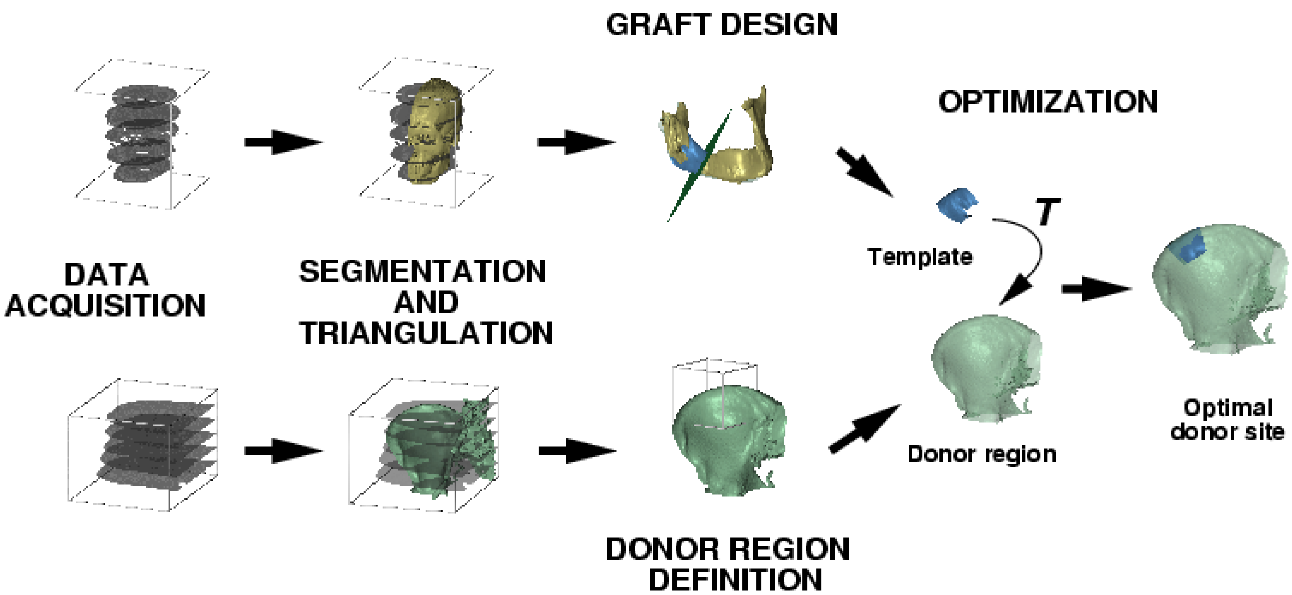

Fig.2. Selection of the optimal donor site for the autologous graft - a computer-aided approach for the graft surgery planning.

2.1. GRAFT DESIGN

After the surgeon has identified the spatial extent of the pathological finding, the shape of the template and the geometrical constraints for the optimization process have to be defined. As already explained the crucial graft design step is performed on the segmented CT datasets. For the segmentation of the osseous structures thresholding, region growing, morphological operations, interactive definition of the region of interest and various filters can be applied to the 3D CT datasets. 3D surface models are generated using the marching cubes algorithm. The surgeon can interactive explore and interact with the virtual patient model. The shape of the graft is defined by using simple cutting planes or cutting volumes. Position and inclination of the cutting tool can be controlled using standard computer mouse and keyboard as well as in a more intuitive way by using three-dimensional input devices. Our planning system has been combined with a haptic interface[6] (PHANToM, SensAble Technologies, Inc., Woburn, MA) (see Figure 3 *(left)*). The 6 degree-of-freedom (6DOF) input is very useful for precise control of position and orientation in 3D space. The cutting plane and manipulation tools are extremely effective given the 6DOF nature of the interaction. For example, the cutting plane can be easily and precisely positioned and oriented within 3D data, which is a particularly difficult problem with the 2D mouse. The designed graft's template can be saved to a separate file. In the case of large bone defects the graft can be designed using a mirror technique (see Figure 3 *(right)*). The healthy side is duplicated, mirrored and aligned with the pathological side. The required graft's shape is then defined in the symmetrically formed template. During this step the surgeon has also to define the donor region in the *donor site* CT dataset (see the bounding boxes in Figure 4).

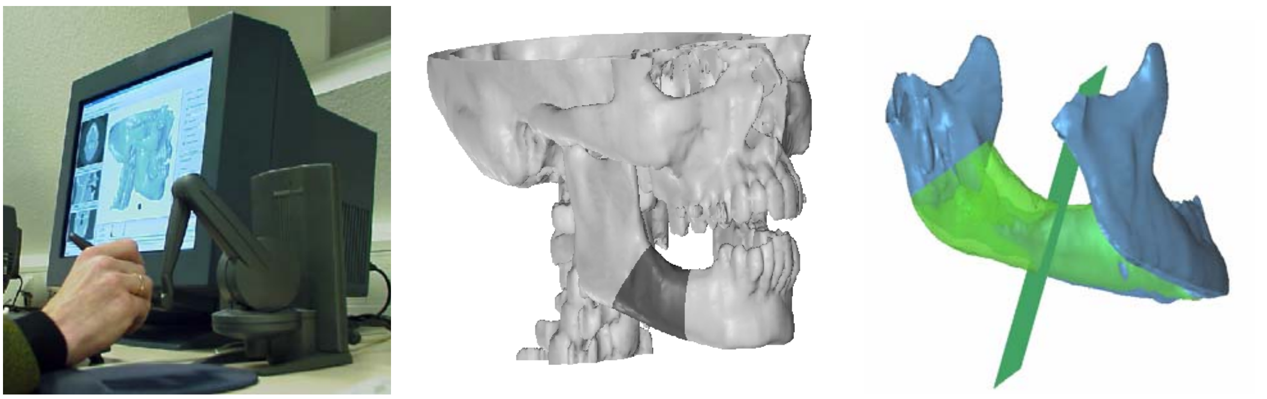

Fig.3. Left: The graphical user interface of the planning system and the PHANToM haptic interface enabling more intuitive interaction between the user and the virtual objects. Middle: Designed graft's template and delineated osteotomy lines after the graft design step (for the case showed in Fig. 1 (left)). Right: Mirror technique applied to the large bone defects (for the case showed in Fig. 1 (right)). The required graft's shape can be defined in the symmetrically mirrored healthy part of the mandible (green).

2.2. OPTIMIZATION

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 *M*[3]. Previously, the simulated annealing[7] – a non-deterministic optimization method – has been applied in our system to solve the optimization problem for all applied misregistration measures. The method is very robust and non-susceptible to local minima. But the drawback is, it is very time consuming approach. Depending on the chosen cooling schedule, on the size of the *template* and the *donor site* datasets and on the applied matching measure the typical running times were between 20 minutes and 5 hours. In the case of surface based fitting technique[2] we have decided to use another approach – the deterministic one. The Levenberg-Marquardt method[8] 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[8]. 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 don't work satisfactorily. The surface based fitting uses intensively Euclidean distances between the position of the *template* surface point **p** after being transformed by T_v and the closest point of the *donor site* surface. By the distance we mean the length of the vector that is defined by that pair of points. To accelerate the distance computation the 3D distance transform method [9] has been applied. We have to keep not only the length but also the three coordinates of the vector, which will be used to estimate derivatives of the objective function in the optimization process. The computation of the distance map is the most time consuming part of the whole process. In some cases we can shorten this time by computing the distance map only for a certain region of interest (see Fig. 4). 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.

3. RESULTS AND DISCUSSION

A computer aided surgical planning system for selection of optimal donor sites for autologous grafts has been developed. 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. By using the haptic interface the graft design step can be performed easier and faster than the standard 2D mouse based approach. It is easy to learn and operate. Different similarity criteria and an efficient optimization method have been implemented. 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 on the computer display using an efficient graphical interface. Besides various 2D techniques to display matched slices conventional surface rendering techniques have been implemented (see Figure 4). The two objects can be also rendered as semi-transparent surfaces. Combining these with volume rendering and introducing a dynamical component significantly enhances the perception of three-dimensionality during the examination and offers a valuable tool in comprehension of complex 3D structures.

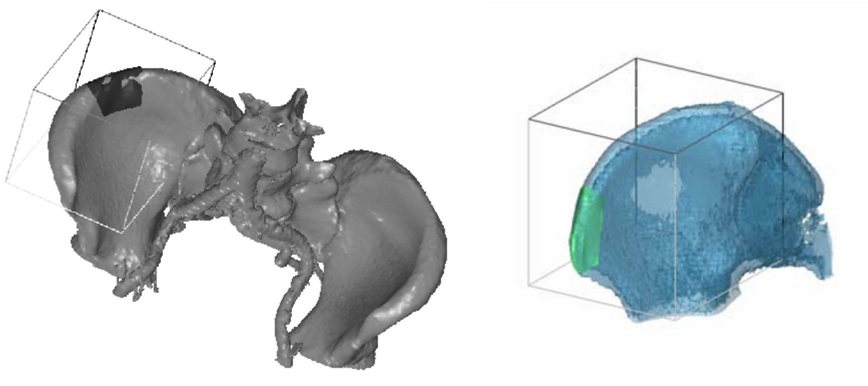

Fig.4. Pelvis with superposed templates (from the Fig. 3 (middle and right accordingly)) positioned at the automatically estimated optimal donor sites.

Our surgical planning system has been written in C++ with a usage of some external libraries. For creating the graphical user interface and for some 2D graphical operations the Qt library has been used. VTK and OpenGL libraries have been used for 3D visualization and real time interaction as well as Ghost library for the haptics. These libraries are fully cross-platform. Thus, the application is fully operating system independent. A reconstructive operation with the 3D planning was performed on 30 patients with osseous defects in different areas of the facial bones. 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. Figure 4 shows a superposition of the to be reconstructed part of mandible with the pelvis donor site. In the Figure 6 the graft (designed in the Figure 3 (middle)) harvested from the iliac crest (left) and fixed rigidly to the recipient site by means of metal plates and screws (right) has been shown. Continuous follow-up observations show that there is less loss of transplants, when they are individually designed as well as high improvement of the functional results like chewing ability by exact reconstruction of dental occlusion. Moreover, in most cases the duration of the surgical interventions has been distinctly reduced due to computer-assisted preoperative osteotomy planning.

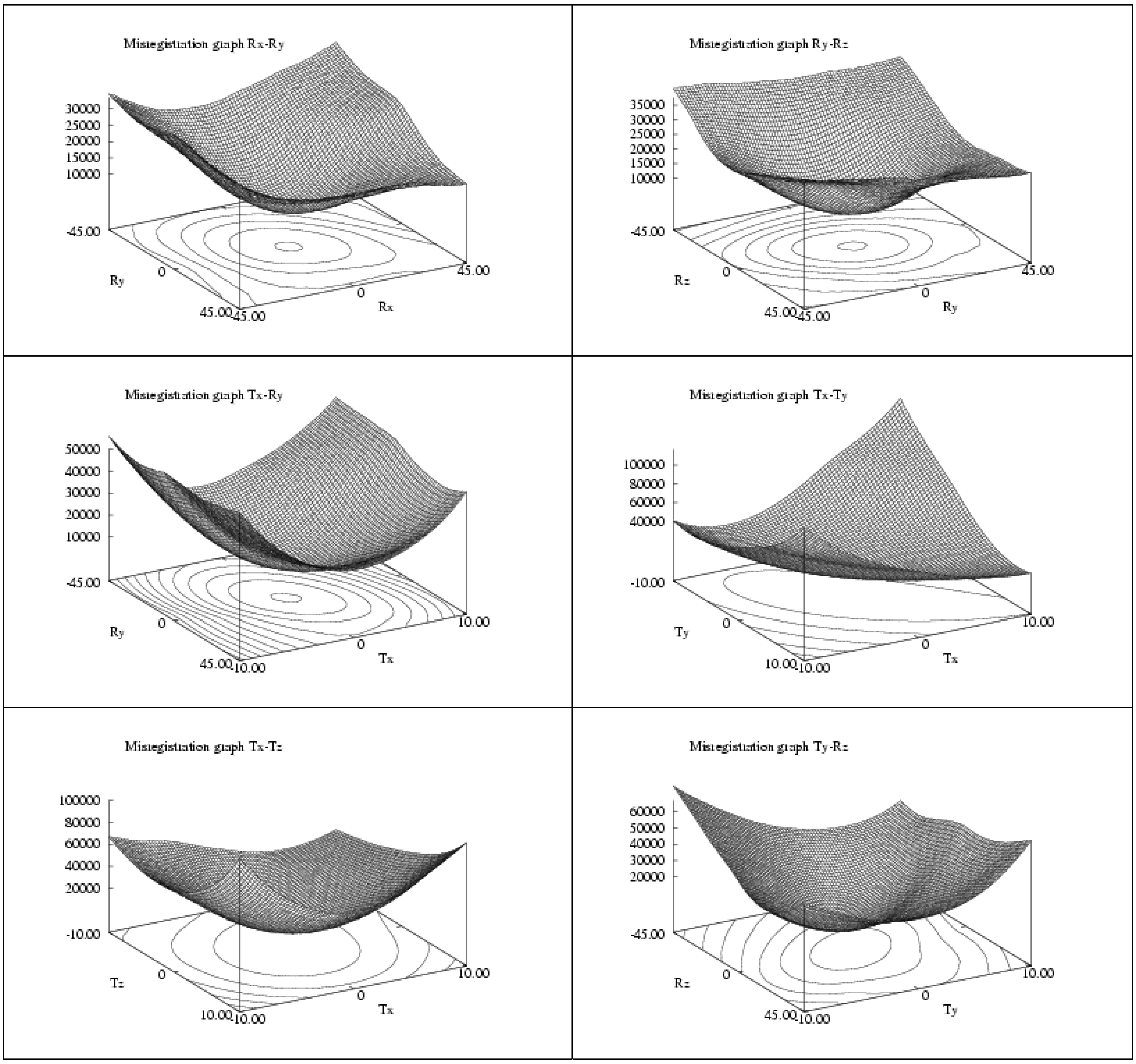

Fig.5. Selected misregistration graphs for the case presented in the Figure 3 (left).

3.1.1. MISREGISTRATION GRAPHS

From the mathematical and numerical point of view the main goal of the registration process is always to find minimum of the similarity function. After the optimization process is completed it is very important to validate obtained result. Many approaches can be applied to solve this problem. One of the most commonly used is the visualization of the misregistration function values in the neighborhood of the estimated optimum. If the function depends only on one or two variables it can be easily visualized using two or three-dimensional graphs. The problem occurs, as in our case, when there are more than two parameters - it cannot be fully visualized in the standard way. In such cases the landscape of the function in the neighborhood of the minimum can be explored using 3D plots - presenting the dependence of the function value on two out of all available parameters. This kind of graph reveals the behavior of the function at the specified range of two variables. In cases where we have function dependent on six variables the number of all combinations of possible plots is 15. One example of the described validation method is shown in the Figure 5. The presented function landscapes have been generated for the case from the Figure 3 (left). The center point of every plot shows the value of the function presumed as minimum. It is clearly visible that any changes made to each of the parameters increase the value of the misregistration function - what can be treated as the visual proof of the donor site optimality.

	Case 1	Case 2
Donor region size	81×108×26	181×185×91
# template points	2589	1677
Preprocessing time	26.5 sec	39.7 sec
Optimization time	14.9 sec	10.1 sec

Tab.1. Running times for the Levenberg-Marquardt optimization method (surface similarity measure) in the two planning cases showed in Fig.1 and Fig. 4. For the same cases the simulated annealing running times (normalized mutual information) were 51 min 17 sec and 109 min 42 sec accordingly.

Fig.6. Designed in the Figure 3 (middle) graft harvested from the iliac crest (left) and fixed rigidly to the recipient site by means of metal plates and screws (middle). The patient 6 months after graft surgery (right).

4. CONCLUSIONS

By using the registration framework a novel surgery planning method has been developed. The method enables computer-aided selection of optimal donor sites for autologous bone grafts in the craniofacial surgery. The main advantage of the method is that after determination of the initial conditions and constraints it provides an automatic procedure to find the best fitting position. The new optimization technique based on the Levenberg-Marquardt method enables, once the pre-processing step has been performed, selection of the optimal donor site in time less than one minute (see Tab. 1). All generated solutions can be explored interactively on the computer display via an efficient graphical interface. Applying different similarity measures enables the surgeon to select the optimal donor site not only in terms of bone surface correlation but also according to the whole volumetric information contained in both data sets. This new approach permits more precise planning of the surgical procedure, reducing intraoperative time and improving the postoperative outcome. The next steps of this work aim on the graft modeling through parametric surfaces and combining our framework with an intraoperative navigation and instrument tracking system to transfer the high precision of the computer-assisted selections of the donor site into the operation situs. A long-term goal is also employing of laser based osteotomy tools, which should enable clean and precise cuts through a bone.

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