A 3-D System for Planning and Simulating Minimally-Invasive Distraction Osteogenesis of the Facial Skeleton

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Abstract. Three-dimensional planning tools will enable the use of minimally-invasive distraction osteogenesis for the correction of craniomaxillofacial deformities by simulating treatment, precisely quantifying movement vectors, and aiding pre and post-treatment evaluation. Current techniques extrapolate 3D surgical movements and outcomes based on standard 2D radiographs. Surgical planning and outcome evaluation would be greatly improved by an accurate, reproducible and reliable 3D treatment planning system. Building upon a software foundation that includes the *3D Slicer* of the Brigham & Women's Hospital, and the Visualization Toolkit (VTK) of Schroeder, Martin & Lorensen, we add algorithms that support interactive cutting of large triangulated surface models, collision detection, landmark-based registration, and cephalometric analysis. The oriented bounding-box tree (OBB tree) structure is used throughout to enhance the interactivity of selection, collision detection, and cutting. The cutting tool is notable for its generality and preservation of topological closure in the resultant models. In a retrospective case study, the collision of the proximal fragment of the distracted mandible with the skull base is detected and the resulting 3D bone movements are quantified. The distracted bone volume is computed. In prospective cases, this system will be used to compute the placement and configuration of appropriate buried distractor(s).

1 Introduction

The success of most CMF surgery depends on careful planning based on accurate diagnostic information. Most orthognathic and craniofacial surgical procedures address skeletal disproportions that are visualized in the mid-sagittal plane, hence the great utility of the lateral cephalometric x-ray in conventional treatment planning. However, for the many patients with asymmetric deformities, projection of the facial anatomy onto the mid-sagittal plane does not permit adequate evaluation and planning,

necessitating 3D analysis [1]. Improved surgical techniques, such as minimally-invasive endoscopic osteotomy and placement of a buried distraction device, further heighten the need for accurate planning tools, which now must compensate for decreased visual access and decreased ability to make mid-treatment adjustments.

Traditionally, surgeons have considered translational and rotational components of a proposed correction separately. These six position parameters, three in translation and three in rotation, are sufficient to characterize the final positions of skeletal components, but do little to address the question of movement path, which is an essential characteristic of distraction osteogenesis. From two reference points, the movement path can be characterized in many cases, using Euclidian principles, as a rotation about a unique axis [3]. When applicable, this provides a way to prescribe both the treatment motion and final position.

Computer tomographic (CT) and magnetic resonance imaging of the human body has had an enormous impact in medicine during the past 20 years. Craniofacial anomalies [7] and fine anatomic details of facial traumatic injuries [14] have been accurately demonstrated with such imaging techniques. Currently, acrylic models of the skull can be created using CT based 3-D imaging and stereolithography. Surgical planning and simulation can be carried out on such models [8,9] Custom alloplastic implant prostheses can be simulated and then produced [10]. However the process of acquiring a 3-D CT scan, producing a model using stereolithography, and simulation on the model is time-consuming and very costly. Furthermore, the axis of a proposed movement can not be accurately calculated, nor can multiple “what if?” simulations be easily carried out.

Interactive surgical simulation technology [11,4] is currently being modified for use in the craniomaxillofacial skeleton. After the CT-data are acquired, bone and soft-tissue segmentation algorithms are applied, and a compression algorithm is used to decrease the size of the data set without sacrificing anatomic detail [16,5] A system that provides the flexibility to simulate any craniofacial skeletal operation has been [5]. This used a planar cutting tool of infinite extent and infinitesimal thickness.

Our goal was to devise a tool that overcame the limitations of prior systems, and that used a conceptual framework that was well-suited for the specific requirements of distraction osteogenesis. Specifically it should:

- Have highly interactive performance in all planning phases.
- Provide clear visualization of the relevant anatomy.
- Permit generalized cutting with realistic tool geometry.
- Create topologically closed bone surface fragments.
- Use collision detection to constrain bone fragment movements.
- Describe the planned movements in an intuitive way.
- Generate a motion plan for each distractor.
- Aid quantitative analysis via cephalometric measurement.

Our current system realizes each of these goals. It is being used for retrospective analysis of about twenty cases. The advantages of our system in cases of hemifacial

microsomnia are evident, and plans are in place to begin prospective cases in the coming months.

2 Methods

2.1 Surface Model Generation

Starting from a high-resolution 3D CT, we use the 3D Slicer [17] to perform semi-automatic segmentation of bone based on an appropriate radiologic threshold. Resolution limitations make false connections between upper and lower dentition, and between mandible and skull at the TMJ common. The incidence of these connections has been reduced by using tensor-controlled local structure enhancement filtering [5], but a fully automatic bone segmentation remains elusive. Therefore, an hour or two of manual refinement is typically required for segmentation.

From this segmentation, the 3D Slicer uses the marching cubes [11] method and triangular surface decimation [16] of VTK [15] to generate triangulated surface models of the facial skeleton, and the skin. The large size of these models, typically 50,000 triangles, requires a data structure that supports $O(\log N)$ triangle location, for landmark selection, collision detection, and cutting. For this we have employed an OBB-tree structure [13], and contributed enhancements to its open-source implementation in VTK.

2.2 Landmark Identification

The operator may select the cephalometric landmarks of interest either by picking points on the resliced plane images provided by the 3D Slicer, or by picking points on the surface model in the 3D window, depending on which representation makes identification simpler. We represent these landmarks visually as “radar reflector” glyphs, composed of three orthogonal squares through the center of an octahedron. We introduce this representation because it has the virtue of clear visibility without obscuring the central point of interest. Picking points on the triangulated surface models is greatly sped up by intersecting the projected ray with the OBB-tree structure. By doing so, only the triangles in OBB-tree leaf nodes that intersect the ray are tested for intersection with the ray.

The selected landmarks are logically identified with the models to which they are attached, so that they are carried with any subsequent registrations or repositionings.

2.3 Data Set Alignment and Cephalometric Analysis

Cephalometric analysis requires that the scan be aligned to a standard orientation. In 2D cephalometric radiographs, this alignment is part of the x-ray procedure. In 3D

CT, the alignment of the scan with the sagittal, axial, and coronal planes is only approximate. If projected measurements are to be accurate, the CT must be aligned to the mid-sagittal and horizontal planes. We accomplish this by identifying three or more points on the mid-sagittal plane, and two or more points on the horizontal plane. Jacobi iteration on the covariance matrices of the selected landmarks provides a least-squares fit to a plane, and Gramm-Schmidt orthogonalization enforces orthogonality between the the vertical and horizontal planes.

With the CT data, surface models, and landmarks registered to standard orientation, we provide a tool for measuring cephalometric distances and angles, either in 3D, or projected onto the sagittal, coronal, or axial planes. Comparison of these measurements with a database of age-related standard values, tempered by the judgement of the surgeon in the particular case, suggests the motions necessary to treat the deformity, and the osteotomy or osteotomies that will be required.

2.4 Simulated Osteotomy

Prior tools for the simulation of craniomaxillofacial osteotomies have been limited in the types of cuts they could perform, and in the representation of the resultant bone fragments as topologically non-closed objects. We address both of these problems with the implementation of a general boolean operation engine for triangulated surface models. This engine can operate in two modes. First, it can rapidly identify collisions between two large triangulated models by colliding the two OBB-tree structures. Second, it can compute the resulting triangulated surface from the subtraction of a tool model from a bone model. This second mode achieves interactive performance by using the prior OBB-tree collision to quickly reject the large numbers of non-participating triangles in the boolean operation.

The core of the boolean engine is triangle-triangle intersection. Each triangle in a leaf node of the two OBB-trees is tested against the triangles from all intersecting nodes by the computation of “piercpoints.” These are the points where the edges of one triangle cross the plane of the other. An intersection occurs if and only if there are four piercpoints, a_0 , a_1 , b_0 , b_1 , which reveal when sorted that the interiors overlap.

Fig. 1. Triangle intersection sorts up to 4 piercpoints, making up to 1 edge.

New edges are generated from intersecting triangles, from which are generated new triangles, which are then organized into a resultant model.

The cutting tool model is positioned with respect to the bone to be cut using a movable coordinate system actor that attaches itself to the tool model and allows

dragging the tool along or around any of the three axes. Once positioned, the cut operation is applied. Additional tool positionings and cuts can be made in the case of multiple or complex osteotomies. The operator then identifies and names each resultant component.

Fig. 2. The cutting tool can have any shape, has finite thickness, and caps the cut objects.

Fig. 3. An overview of the general cutting algorithm

2.5 Reposition with Collision Detection

The next step in simulated treatment planning is the movement of each bone fragment to the new position. Using the same movable coordinate system interface that was used to position the cutting tool, each skeletal component is translated and rotated until visual inspection and re-computation of the cephalometric measurements from the repositioned landmarks indicate the desired correction has been achieved.

While the bone is being moved, the boolean engine is used in collision detection mode to test for collision between the moving bone and the stationary skeleton. Collision is indicated with a beep and a color change in the models that have collided.

On a Sun Ultra-10 workstation with Elite3D graphics acceleration, 3-20 collision detections per second is typical, with a strong dependence on the closeness of approach and the number of triangles.

2.6 Motion Vector Description

Several different conceptual frameworks can be used to capture the six degrees of freedom of three dimensional object repositioning, each with different strengths and weaknesses. For minimally-invasive distraction osteogenesis, where the repositioning will be done by a distraction device placed by a surgeon, a primary consideration is intuitive accessibility, simplicity of motion path, and translatability to an implantable distractor prescription.

We describe the repositioning of points on bone fragments as helical movement around and along a cylinder of arbitrary orientation in three dimensions. The equation of this axis captures four degrees of freedom. The rotation angle around the axis captures the fifth, and the translation parallel to the axis captures the sixth. This representation is reasonably informative to the intuition, describes both the net motion and a simple path, and translates directly to a prescription for an implantable distractor. In the case of simple translation without rotation, the solution is degenerate, so an axis through the origin and parallel to the direction of motion is chosen.

Fig. 4. Repositioning in 3-D is captured by helical movement, degenerate when $\theta = 0$.

For each osteotomy, three sets of repositioning parameters, or prescriptions, are of interest. First is the movement of the distal fragment, which in hemifacial microsomia is typically a rotation around an axis through the unaffected chondyle. Second is the movement of the proximal fragment. Third is the combined movement of the proximal fragment relative to the distal portion, which combined with placement information provides the prescriptive parameters for a buried distractor that will perform the desired repositioning when placed across the osteotomy.

Starting from the matrix representation of the bone repositioning, a 3×3 rotation matrix $\mathbf{R}$, and a translation vector $\mathbf{t}$, quaternion methods are used to determine the direction of the rotation axis. A quaternion $[x, y, z, w]$ is a 4-vector whose xyz portion

is along the unit axis of rotation, $\mathbf{v}$, and whose component w is equal to the cosine of half the angle [18].

$$\mathbf{q} = [\mathbf{v} \sin(\theta/2), w \cos(\theta/2)]$$

With the axis direction and rotation angle determined, it remains to compute a point on the axis and the movement's projection along the axis. The vector $\mathbf{t}$ is decomposed into a component along the axis, $\mathbf{t}_a$, and a component perpendicular to the axis, $\mathbf{t}_p$. The product $\mathbf{t}_a \cdot \mathbf{v}$ is the distance parameter and the latter is substituted into the following equation for finding the rotation center $\mathbf{c}$, which is unchanged by $\mathbf{Rt}$:

$$\mathbf{cR} + \mathbf{t} = \mathbf{c} \quad \text{or} \quad \mathbf{c}(\mathbf{R}-\mathbf{I}) + \mathbf{t} = \mathbf{O}$$

However, with any point on the axis being a solution ($\mathbf{R}-\mathbf{I}$) is not invertable in three dimensions. A unique solution is forced by replacing the smallest column vector of ($\mathbf{R}-\mathbf{I}$) with $\mathbf{v}$, thus imposing the additional constraint $\mathbf{c} \cdot \mathbf{v} = 0$, making $\mathbf{c}$ the closest solution to the origin. We now have the full set of repositioning parameters: $\mathbf{c}$, $\mathbf{v}$, d , θ .

2.7 Post-Treatment Scan Registration & Evaluation

The evaluation of post-treatment scans, for comparison with pre-treatment or simulated post-treatment models, requires the registration of the corresponding non-moving anatomy. We use a rigid, landmark-based registration that performs a least-squares fit of the corresponding landmarks using singular value decomposition [19]. The most reliable non-moving landmarks vary from case to case, so the operator selects corresponding pairs of preselected cephalometric landmarks that are judged to be unchanged by the treatment interval, or by differences in patient position. By selecting a large number of widely-spaced landmarks, the errors in repeatability tend to cancel, making sub-voxel accuracy attainable.

Thus registered, the predicted and actual cephalometric quantities can be compared. Moreover, the visual superposition of the two models allows for a more general qualitative evaluation of the treatment.

3 Results

3.1 Illustrative Case

A seven year old boy with hemifacial microsomia affecting the left side, presents a shortened left mandibular ramus, which is constraining the growth of the maxilla and is interfering with bite function. We compare the actual treatment result using a conventional treatment planner and a semi-buried distractor with the simulated result of a plan created with our system.

When comparing the 3-D treatment plan with the conventional plan and its result, several advantages of the 3-D system are immediately evident. First, using the conventional planner it was not possible to accurately predict the upward movement of the proximal fragment, nor was it possible to predict that the motion-limiting collision would be the coronoid process against the skull base, rather than the hypoplastic chondyle against the fossa. Both of these predictions were readily seen in the 3-D planning process, thus avoiding an undercorrection. Second, the vectors of movement are readily available from the 3-D planner in a form that translates directly to a distraction device. Third, the ability to freely manipulate skeletal components around and along all axes, constrained by simulated bony collision, makes is easier to visualize and reach a functional and aesthetic result.

Table 1. The performance of both cutting and collision detection ranges from around 3 to 150 frames per second, thus ensuring smooth interactivity. These figures are from a Sun Ultra-10 with SunOS 5.7 and elite3D graphics acceleration.

Cutting Performance	
# of triangles	44,090 (mandible) + 12 (cutter)
OBB-tree preprocessing time (ms)	3,358 (mandible) + <1 (cutter)
cutting time (ms)	316
# of intersecting OBB leaf nodes	81
# of triangle-triangle tests	807
# of new edges	307
Collision Performance	
# of triangles	171,994 (skull) + 2,361 (prox.mandible)
collision detection time (ms)	6 to 200
# of intersecting OBB leaf nodes	0 to 35
# of triangle-triangle tests	0 to 130

Fig. 5. Having used selected landmarks to perform least-squares alignment to the mid-sagittal and horizontal planes, A-P and L-R views allow visualization and analysis of the deformity through the measurement of distances and angles between landmarks.

Fig. 6. After simulated cutting, the proximal fragment is moved upward, slightly leftward, and pitched forward a little to avoid the premature collision with the skull base that was detected. The distal fragment is rotated about the center of the right chondyle until functional and aesthetic constraints are satisfied.

Fig. 7. The simulated post-treatment mandible is shown. The gray line is the 3-D axis of the helical motion. The object in the gap is a section of the surface along which a point at the edge of the osteotomy travels. It captures the geometry of the drive track for a buried distractor placed at that point.

Fig. 8. Rigid registration on 6 pairs of unchanged landmarks, (3 shown), between a simulated post-treatment coronal scan and the actual post-treatment axial scan highlights the good fit in the unchanged skull (avg. distance 1.55mm), and areas where the simulated and actual treatments were different. (Bones from the actual treatment are in darker colors.)

4 Discussion

While the 3-D system presented offers a number of valuable planning tools for craniomaxillofacial surgery, it is also intended to serve as a platform for additional capabilities. It is possible to interface the 3D Slicer to a 6 degree of freedom mouse, or even a haptic interface that will provide force feedback when collision or cutting occurs, and can even be made to model the forces from soft tissue. Another important area for minimally-invasive surgery is in intraoperative navigation. One approach that has been used in another 3-D CMF treatment planning system [12] is the stereolithographic manufacture of a hole-drilling template from the CT data. However, this approach requires direct visual access to the bone surface, something that is not available with an endoscopic procedure.

By choosing a helical concept for motion planning, it was hoped that both intuitive appeal and appropriate physiologic distraction will be achieved for the majority of cases. One additional benefit of this approach is that it suggests a design for a general family of distractors that are simple to manufacture with precision and strength. Our approach is different from earlier distraction planning systems in that the desired path is computed first, and the appropriate device is selected second. Earlier work has taken the device as a given, and then computed the necessary adjustments for executing the treatment plan. It is hoped that by making the planning phase device-independent, and having a sufficiently rich family of distraction devices, the treatment plan will be simpler and more robust to execute.

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