AN INTERACTIVE PLANNING AND SIMULATION TOOL FOR MAXILLO-FACIAL SURGERY

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We present a chain of software tools designed to help to plan and predict the outcome of distraction osteogenesis operations in maxillo-facial surgery. The chain starts off with a CT image of the patient's head, which is segmented and used to produce a surface mesh of the skull. Next, the surgeon interactively defines the cuts and the parameters of the distraction process. This information together with the CT data are used to generate a finite element (FE) mesh, including boundary conditions, prescribed displacements or forces. After the FE problem is solved on a remote high-performance compute server using linear or non-linear solution methods, the resulting displacements of bones and soft tissue can be visualized in various ways in order to assist the surgeon in designing the appropriate surgery operation. The entire tool chain is developed as a Grid application with the overall aim of making advanced simulation accessible to the non-technical clinician, providing transparent and secure access to remote computing facilities via a novel layer of middleware.

1. Introduction

Severe malformations of the midface such as maxillary retrognathia or hypoplasia can be treated by distraction osteogenesis. During an operation the appropriate bony part of the midface is separated from the rest of the skull (osteotomy) and slowly moved into the ideal position by way of a distraction device (cf. Figure 1). Thus even large displacements over 20 mm

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can be treated effectively.

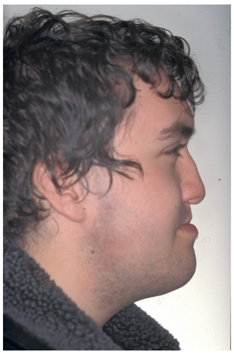

Figure 1. Patient before treatment (left) and at end of treatment with distraction device mounted (right).

A critical point in this procedure is osteotomy design and the resulting outcome with respect to aesthetics. In the current clinical practice, planning is based on CT scans and the surgeon's experience. Our tool chain allows the surgeon to specify arbitrary cuts of facial bones (pre-processing), to simulate the displacements of bones and soft tissue, and to visualize the results in an appropriate way (post-processing). It therefore provides the possibility to predict and compare the outcome of different surgical treatments *in silico*.

The overall goal of our approach is to give the average clinician access to the advanced simulation technology of such surgical planning tools. Physicians typically lack both technical expertise and time needed to prepare input for numerical simulations. Nor do they generally have access to the necessary HPC (high performance computing) hardware and software.

Thus, a successful approach must provide a specialized toolchain which performs the necessary preprocessing tasks autonomously — except the proper "virtual surgery" — and gives transparent and secure access to remote HPC resources. The GEMSS project [3], of which the present work is a part, develops middleware aimed at solving these problems, thus bringing advanced simulation services closer to the practitioner's desktop.

A number of researchers have obtained results in the field of computational maxillo-facial surgery planning. Koch [5] describes a system based on linear elasticity, where osteotomies are specified on 2D pictures. Schutyser et al [8] use a 3D "virtual knife" and emphasize the real-time aspects of simulation, trading accuracy for speed. Zachow et al [11] use a specialized version of the Amira visualization system for most parts of the toolchain, including mesh generation. Simulation is restricted to linear FEM models. Gladilin [4] extends these linear models to first non-linear FEM simulations of the distraction process, using a St.Venant-Kirchhoff material model.

Our approach is different since it is focused on autonomous usage by non-technical users, offering transparent access to high-performance platforms, thus enabling the user to employ compute-intensive, high-fidelity numerical methods (cf. Sec. 4).

The rest of this paper is organized as follows: In Sec. 2, we give an overview over the components of the toolchain. Section 3 discusses in some detail the interactive osteotomy tool. Then, we give some background on the FEM simulation in Section 4.

2. A Toolchain for Maxillo-facial Surgery Planning

For the complete task of maxillo-facial surgery planning and simulation, a number of sub-tasks have to be solved. The raw CT image has to be segmented, and optionally registered to a template head image. Next, a geometric 3D representation of the bone surface is generated from the image, which is handed over to an interactive surgery specification (bone cutting) tool. The output of this tool must be checked for consistency and incorporated into a volumetric FEM model. This step involves 3D mesh generation, application of boundary conditions and additional mesh checking, e.g. for spurious disconnected components. Then, the FEM simulation is run, and finally the results are visualized and interpreted by the surgeon.

Now, clinicians typically are not experts in image processing, meshing or FEM simulation. So, most of the toolchain should run in an automated way, with the obvious exception of the bone cutting task, to be described in the next section. Some of the tasks, most importantly the FEM analysis, but possibly also mesh generation, require substantial computing resources which are generally not available at clinics and may be difficult to use (e.g. supercomputers or clusters). Thus, transparent access to remote computing facilities is necessary. On the other hand, some surgeons may already routinely use some third party software, such as volume visualization, for their surgery planning, and may want to incorporate such tools into the toolchain. Also, when improved or new functionalities become available, it is useful to be able to easily replace existing tools or to offer the new tools as an alternative.

These considerations led us to a highly modular toolchain composed of loosely coupled components, as opposed to a monolithic maxillo-facial surgery planning application. We use the Triana workflow editor [10] to manage the toolchain. Triana offers easy workflow configuration via a graphical programming language, and is also suitable to wrap remote execution of tools in a transparent way, for instance via the GEMSS middleware [1].

3. The Virtual Bone Cutting Tool

A crucial step in the toolchain is the specification of bone cuts and displacements. A suitable tool for this task should have the following properties:

- It should not impose constraints on the number of displaced bone components and the displacements
- It is ergonomic and supports the user by giving visual feedback on the user input
- It provides quantitative aids like lengths measurements

We choose to build our cutting tool on top of OpenDX [7], because it offers a wide range of visualization features and sufficient interaction capabilities. Also, it is easily extensible by user-provided modules. This approach has the advantage of quickly arriving at a working prototype.

The flow of action within the cutting tool is as follows: First, the user specifies a number of cuts as closed polygons by selecting points on the bone surface, which is represented by a surface mesh. Then, he chooses bone component(s) to be distracted, and specifies the corresponding translation(s) and rotation(s). An important feedback we plan to integrate in the near future is the visualization of the displacements by moving the components to their specified positions.

After all cuts have been specified, they are converted into three-dimensional volumes which are used to actually apply the cuts on a volumetric model. The conversion takes place in two steps: First, the non-planar polygon is triangulated, and second, this triangulation is extruded using the normal directions at each vertex, with a user-specified thickness.

The complex geometry of the human head may turn the placement of cuts into a tedious problem. In order to support the surgeon, we provide clipping planes and selectable transparency of the bone. In addition, the 3D location of the cuts is visually emphasized by using balls and tubes for the vertices and edges of the polygons, see Fig. 2.

Another difficulty is the verification of the separation of components. It may happen that parts intended to be separated by cuts are in fact still connected by small bridges, which would grossly distort the subsequent simulation. A possible source of such bridges may be segmentation artifacts such as the missing separation of upper and lower teeth. For finding such bridges, we have developed a coloring tool which colors a component in a wavefront starting from a selected seed point. A bridge will than be detectable as a “color leak” (cf. Fig. 3).

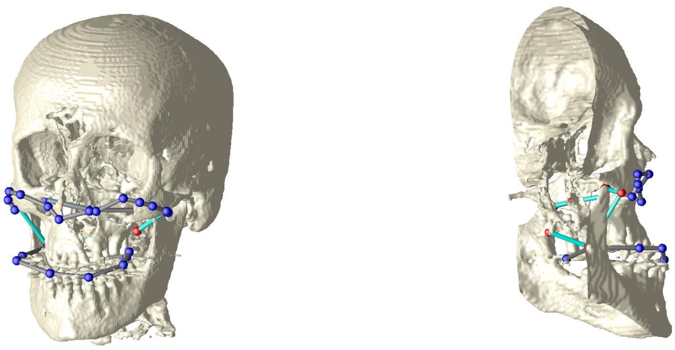

Figure 2. The cutting tool: Front view (left) and side view with clipping. The current cut is highlighted. The cut separating lower and upper jaw is neccessary to overcome segmentation artifacts introducing unphysical connections

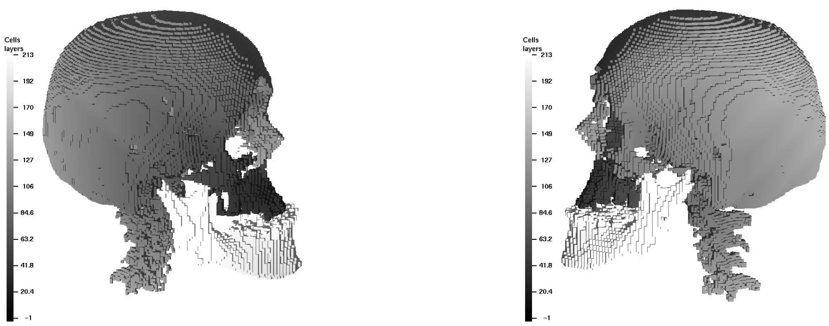

Figure 3. Visualization of bridges by using a wavefront coloring of components. It is clearly visible by the continuous coloring that the maxilla is not entirely cut in the right part (left image). It is also visible that the lower jaw is separated from the rest of the skull.

4. Distraction Simulation

The simulation of the distraction process is done by a Finite Element analysis. Both time and memory requirements of such an analysis are far beyond the capabilities of a single workstation or PC and are therefore carried out remotely on a parallel machine via the GEMSS middleware. The memory requirements depend on the resolution of the mesh and on the memory consumption of the linear solver, Since our FE discretization uses displacement based elements like linear or quadratic tetrahedra and hexahedra, the number of unknowns in the resulting linear systems is approximately 3-6 times the number of elements. Typical meshes consist of 10^5 to 10^6 elements, resulting in memory requirements grossly ranging from 3 GByte to 30 GByte for linear elements. In order to solve the resulting systems we use iterative solvers, namely preconditioned Krylov subspace solvers. We use algebraic multigrid preconditioning if possible, since it shows optimal complexity and ILU preconditioning if necessary, which is a more stable but less fast method.

The user can choose between different levels of elasticity models. For a fast but possibly rough estimation of the resulting soft tissue deformations we supply a linear elastic material model. In order to enhance the accuracy we discretize the resulting equations with highly efficient EAS elements [9]. A linear problem with 100,000 elements is solved in about 5 minutes on 16 nodes of a PC cluster with an AMD Athlon 1900+ CPU and 2 GB of memory at every node.

For a more detailed analysis, the user has to provide details about the distraction process in time, i.e. details about the velocity of the prescribed displacements or the time dependent changes of the distracting forces. Here the material is modeled by a viscoelastic material law, based on a geometrically nonlinear hyperelasticity. These computations last several hours, but give the surgeon a detailed view on the development of the resulting displacements, forces and stresses in time. Non-linear computations are crucial for obtaining realistic value for the relations between displacements and forces / stresses.

Right now we distinguish between bone and soft tissue and model both materials by isotropic laws. In the future we are planning to incorporate additional information from the CT image and a template head model based on combined CT and MR data in order to get a more realistic distribution of the material parameters. Those parameters and the use of specialized material models for skin, muscles and other kinds of tissues are expected to further improve the accuracy of our simulations. For details on more complex models the reader is referred to [2] and [6].

Figure 4. Patient before treatment (left) and simulated surgery (right), using volume rendering of original and deformed CT image

5. Conclusion

The presented tool chain enables the surgeon to predict the outcome of a distraction osteogenesis for an arbitrary set of cuts and distractions and is therefore a valuable tool for planning such treatments. By using advanced Grid computing infrastructure, the crucial time and memory intensive parts of the tool chain can be executed remotely on a HPC server. This enables the surgeon to get results from adequate state-of-the-art simulation within acceptable times, without needing to worry about technical details or security issues.

The development of the tool chain is still ongoing work. The clinical evaluation of the tool is still pending and we are looking forward to improve the tool by incorporating feedback of the medical experts who are testing it. In particular, we plan to make the cutting tool more ergonomic by offering automatic fitting of cut lines to the skull surface geometry, and to use registration of a template head to import auxiliary data like clipping etc. Another important improvement will concern removal or reduction of metal artifacts which may distort the simulation. We also plan to use a registration approach to map more soft tissue details like muscle strings, and to compare quantitative differences between simulations run with different material laws and resolutions. This will give us a clearer picture of the tradeoffs between computation time, sophistication of material modeling and accuracy of simulation.

Acknowledgments

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