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A Simulation Tool for Maxillo-Facial Surgery based on Finite Element Methods and Algebraic Multigrid

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In this paper we describe a chain of computational tools (Maxillo-Facial toolbox) for the simulation and planning of Maxillo-Facial surgery, known as distraction osteogenesis. This surgery is performed to correct the configuration of the bones of the midface of a patient. Therefore some of the bones are cut and are given new positions. The repositioning of the bones can be completed during the surgery or, if the displacements are large, after the surgery by a pulling procedure that can last several weeks.

While the final position of most of the bones is determined by medical needs, the final shape of the facial tissue is not known a-priori. Often additional plastic surgeries are necessary to correct the outcome of the initial distraction. Our tool chain simulates the displacements of bones and soft tissues and therefore provides the possibility to plan the surgery in a way that the final shape of the facial tissues satisfies patient and surgeon. The tool chain consists of the following parts:

The first tool of our simulation environment is a segmentation step that takes a CT image of the patient's head as input and labels the volume data into different anatomical structures. Then we generate a surface mesh of the bone volume and use it as input for our virtual bone cutting tool.

With the cutting tool the surgeon defines abitrary 3D cutting paths to cut out parts of the skull and define their new positions.

The next tool in our chain creates a volume mesh based on the image data of the head and incorporates the cuts and prescribed displacements. The output of this tool is a Finite Element mesh of the head and a set of boundary conditions corresponding to the prescribed cuts and distractions.

In our main tool this mesh is used to simulate the distracting process by our

parallel Finite Element code which is combined with a fast multigrid solver and can use a variety of material laws (linear elastic, hyperelastic, viscoelastic) and different Finite Element formulations (linear, quadratic, mixed elements of tetrahedral, hexahedral and pyramidal shape). By using different discretizations our tool can provide simulations of varying accuracy, starting from linear, static and very fast simulations, that are used to provide a first impression for the surgeon, up to very detailed ones that take into account non-linearities and time dependencies of the underlying problem and need several hours of computing time. The ability to vary the accuracy of the physical model and its discretization is highly required by the physicians and one of the major advantages of our tool. In a last step the results are downloaded and post-processed.

In this paper we focus on the details of the parallel Finite Element code. We show how our improvements in both areas from static linear elastic models to time dependent viscoelastic ones lead to more reliable results for the surgeon. We will also present our experience in combining different discretization methods, such as pure displacement elements or mixed elements, with different linear and non-linear solvers. We will show that in order to build an efficient and robust simulation tool one has to choose the combination of models and solvers very carefully.

Keywords: Biomechanic, Maxillo-Facial Surgery, Parallel Finite Element Method, Nonlinear Elasticity, Algebraic Multigrid