Recent advances in medical imaging and surgical techniques have made possible the surgical correction of severe facial deformities and fractures. Surgical correction techniques often involve the direct manipulation – both relocation and surgical fracture – of the underlying facial bone. Several projects (e.g. [1], [2], [3]) have focused on the simulation of such craniofacial surgical procedures, although the focus of most previous work has been on the prediction of soft tissue movement and the prediction of post-operative facial appearance given a series of bone manipulations. The surgical procedure itself is typically represented as a series of geometric operations – defined via explicit cutting planes or analytically-specified transformations – performed on a surface representation of a bone model. Little work has focused on real-time simulation of relevant procedures.

The work presented here introduces an environment for interactive, visuo-haptic simulation of craniofacial surgical procedures. The simulator is intended for both training and procedure-specific rehearsal, and can thus load canonical training cases or patient-specific image data into the interactive environment.

Isosurfaces are generated from CT or MR data using the marching cubes method ([4]). A flood-filling technique is then used to build a voxel grid from the isosurface data. Voxel data is then loaded into the interactive simulation environment, in which a SensAble Phantom ([5]) haptic device allows the user to control a virtual tool with realistic force feedback. The virtual tool set includes a series of bone drills and levers that allow interactive manipulation of the bone volume (see Figure 1). Our haptic feedback and graphic rendering techniques are described in more detail in ([6]).

A critical step in simulating craniofacial procedures is the detection of cuts in the bone volume that separate one region of bone from another, thus allowing independent rigid transformations to be applied to the isolated bone segments. Previous work has performed cut detection in a triangulated surface domain; we use a dynamic flood-filling technique to detect separation of bone segments in our volumetric data structure. This allows us to detect cuts in the volume, which allows the user to move and rotate isolated bone segments. Additionally, for the simulation of osteosynthesis techniques, we incorporate 3D models of several Synthes plates and other relevant surgical hardware (e.g. bone screws) into the system. This allows users to plan and practice plate-insertion operations interactively, using industry-standard plates.

Another goal of our simulation environment is to train the surgical skills required to avoid critical and/or sensitive structures when using potentially dangerous tools. We thus incorporate a virtual nerve monitor that presents the user with a representation of the activity of nerve bundles in the vicinity of the procedure (Figure 2). Nerves are currently placed explicitly for training scenarios; the automated detection of nerve bundles in medical images is a difficult problem.

Initial work with surgeons indicates that the haptic feedback associated with bone manipulation is quite realistic. Future work on this project will thus focus on the incorporation of soft tissue data. Online soft tissue representations will be critical for the simulation of constraints imposed on bone movements, and for the training of complete procedures including incisions and soft tissue displacement. Offline soft tissue simulation will be critical for incorporating previous work in the prediction of soft-tissue appearance following craniofacial surgery (e.g. [1],[2],[3]). Furthermore, we hope to extend our simulation of sensitive structures; a representation of potentially sensitive blood vessels will be important, as will the automated or semi-automated extraction of such structures directly from image data.

---

**Figure 1**: Interactive modification of bone volume. Using the haptic device, the user brings the virtual tool in contact with the bone and interactively begins a cut through the bone volume.

**Figure 2**: Interactive monitoring of virtual nerves. When the virtual tool makes contact with the bone in the vicinity of the virtual nerve bundle, a series of neural pulses is presented via graphic and auditory monitoring tools. Several such bursts are displayed in the above clip, captured from the graphic monitor.

---