

Orthopedic Surgery Training on Personal Computer

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Abstract

Surgical training is one of the most promising areas in medicine where 3-D computer graphics and virtual reality techniques are emerging. This paper provides an advanced report on our project that aims to create virtual reality tools for training medical students and for improving skills and efficiency of orthopedic surgeons in internal fixation of bone fractures. The paper describes the whole pipeline from the CT scanner through the Unix-workstation to the personal computer where eventually the program works. We also describe the methods and mathematical models that allowed us to implement the ultimate goal of the project—to allow the surgeons to perform training surgical operations even at their home computers without any special expensive hardware devices. This project was initiated in Singapore and currently continues as an international project.

Keywords: *surgery training, virtual reality, orthopedics.*

1. INTRODUCTION

Surgical training is one of the most promising areas in medicine where 3-D computer graphics and virtual reality techniques are emerging. Attention of researchers has now turned toward using combined 3-D reconstruction and virtual environment (VE) technologies to train clinicians and to help surgeons plan patient-specific, complex procedures in craniofacial reconstruction and plastic surgery, surgery for trauma from accidents, breast cancer detection, and reconstruction surgery [1-6]. In surgery simulation for training the clinicians, the benefit of savings in time, cost, equipment, and safety can be enormous. As a result, there is a growing interest in applying VR simulation technology to the medical educational process.

Surgical simulators are used to create a VE wherein the surgeon may simulate and plan the operation, and the surgeons or students can be trained. One of the main problems is to receive a photo-realistic representation of operation room, human body parts from CT or MRI data, surgical instruments and implants. Sound can be imposed into the scene to add realism. For example, sound of drilling has been added in VE of craniofacial surgery simulation

[1]. Virtual surgery is often performed with tissue and blood [5-8]. For example, the training system KISMET [7,8] provides simulation techniques, which allow the modeling of “virtual tissue”, based on a data-model which reflects the physical characteristics like mass, stiffness and damping of real tissue. However, for orthopedic surgery, it is not necessary to simulate the soft tissue except of some cases in craniofacial surgery. For example, it is important to know the result of bones replacement covered with tissue in craniofacial surgery. When all the reconstruction work is completed, the soft tissues are replaced so that the surgeon can visualize the result. If the outcome of the virtual surgery is not desirable to the surgeon, the virtual process can be repeated until satisfaction is obtained, without touching the patient. In surgical simulators, a collision test algorithm for detection of the contact between surgical instruments and the virtual organs is often performed. In the training system KISMET [8], contact forces between the tissue and the instrument end-effector are calculated which can be used to drive a force-reflecting surgeon interface 3D-simulation support during the design of new surgical instruments and manipulator.

A comprehensive software system for interactive visualization, manipulation and measurement of multi-modality 3-D medical images has been developed, used and evaluated at the Mayo Clinic for Computer Aided Surgery and Radiation Treatment Planning for more than a decade [9,10]. This software system, called ANALYZE, has provided surgeons and physicians with powerful and flexible computational support both for pre-operative surgical and treatment planning and for post-operative evaluation. The software has been applied to a variety of surgical and medical problems, and used on significant numbers of patients at the Mayo Clinic and at many other institutions.

The training systems available on the market are oriented on solving the particular problems. For example, Limb Trauma Simulator (Musculographics Inc.) models a gunshot wound to the leg for military surgeons training [11]. Software for VR Surgery mainly works on UNIX on Silicon workstations or is prepared on the powerful workstations. For example, Voxel-Man Junior is a subproject of the general VOXEL-MAN-project aiming to transfer substantial functions of exploring and manipulating 3D

anatomical models from the workstation based VOXEL-MAN system to inexpensive PCs [12,13].

In this paper, we address the problem of developing virtual reality tools for training medical students and for improving skills and efficiency of orthopedic surgeons in internal fixation of bone fractures. We developed a desktop VR orthopedic surgery training system capable of running on commonly available PCs including notebooks without compulsory use of VR hardware.

2. THE PROBLEM STATEMENT

During common orthopedic surgery training, students must fix fractures on synthetic plastic bones using surgical tools and implants. Figure 1 shows a typical fractured plastic bone. These synthetic bones differ in quality and cost. Good-quality synthetic bones aren't just simple plastic dummies. They are made from the materials with different densities and textures on the surface and inside to simulate real bones as closely as possible.



Figure 1: Fractured synthetic bone.

Normally, students assemble the bone in front of them, in the position typical of the respective real operation. Then, they reduce the fracture and fix it internally using implants that include hundreds of different plates, screws, nails, and wires. See Figure 2, for example, where the fractured femur is fixed with the nail inserted in its canal and with four screws. For the insertion of implants, students—or surgeons—use different surgical instruments that let them drill holes, measure for a length, insert the implants, and so forth. The training lab with all this stuff looks rather like a repair shop. There is no flesh and blood there, or anesthesia and assisting nurses. Each student works along independently.

The objectives of this orthopedic training follow:

- To memorize the techniques and respective tools and implants used for fixing fractures, and to choose the most relevant technique for each case.
- To learn how to put the implants in place, including exactly where and how deep to drill or cut the bone, the proper insertion angle, and so on.
- To acquire “muscle memory” for the physical efforts applied to the tools and implants to avoid damaging the bones.



Figure 2: X-ray of the fracture and its fix.

Many synthetic bones are spoiled before a student can demonstrate the necessary skills on this “synthetic patient.” The next step is surgical operations on cadavers. Only after that is the student allowed to approach a real patient.

The idea of using a computer for orthopedic surgery training came from surgeons in the Department of Orthopedics of Singapore General Hospital, who approached the School of Applied Science at Nanyang Technological University. The surgeons were interested, first, in saving the cost of the bones—good-quality synthetic bones are expensive—and second, in the ability to work with certain types of bones for which synthetic models might not be available. The latter need also derived from the fact that real Asian bones have their own geometric specifics compared to the commonly available synthetic bones. Besides that, the surgeons anticipated an attractive possibility—training the students on virtual models of real fractures obtained from computed tomography (CT) or magnetic resonance imaging (MRI) data.

Our feasibility study assured us that at least the first two objectives of the common orthopedic training could move into the virtual environment relatively easily, with the outside possibility of complete virtual orthopedic surgery training if special haptic devices were used. Certainly, this virtual training won't substitute completely for the compulsory training on synthetic bones and on cadavers, but it might let the students perform the initial routine work entirely in the virtual environment, thus saving cost and time.

To make this virtual training easily accessible, we decided to develop a software system capable of running on PCs, available in every medical clinic and in homes. This desktop or “pocket” VR system had to produce acceptable realism even without special VR input devices such as head-mounted displays (HMDs) or goggles, although using them obviously would provide better immersion.

Eventually, we came up with a project aiming to develop an inexpensive alternative to common orthopedic surgery training that would allow the surgeons the following:

- To keep in the computer every single bone of different sizes and specific features that might be difficult and expensive to obtain using synthetic models.
- To create models of the fractured bones from real patients using data from CT and MRI images.
- To perform surgical operation planning before undertaking the actual operation.

3. VIRTUAL ORTHOPEDIC SURGERY TRAINING

First initial reports on this project were published in papers [14-16]. In this paper, we provide an extended report on the project describing the whole pipeline from the CT scanner through the SGI-workstation to the personal computer where eventually the program works. We also describe the methods and mathematical models that we used for implementing the ultimate goal of the project—to allow surgeons to perform virtual surgical operations even at their home computers without any special expensive hardware devices.

Achieving immersion in most VR systems usually requires the following:

1. Realistic 3D geometric models with behavior and constraints.
2. Real-time simulation including collision detection, sounds, and so forth.
3. Real-time 3D rendering.
4. VR rendering and input techniques based on special hardware devices.

Since we aimed to develop a system capable of running on PCs including notebooks without compulsory use of VR hardware, we concentrated on the first three requirements at the current stage of the project. Also, while designing the system, we kept in mind the significant difference between computer-assisted surgery and training systems. The former assist and guide the surgeon during the real surgery operation, while the latter simulate only certain aspects of these operations with a sufficient degree of realism.

In the virtual environment, the orthopedic surgeon deals with models of bones, surgical tools, and implants. Fixing fractures requires using certain virtual fixation techniques. To achieve our goals, we had to find a reasonable balance among the processing time, the size, and the complexity of the models and techniques.

4. THE DATA PIPELINE

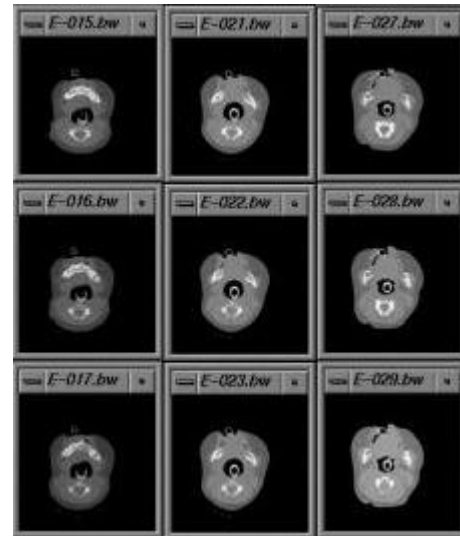
Except for cases where the data for reconstruction of the bones, the tools, and the implants come from the atlases or third parties, the following pipeline was developed for the project.

Initially, the CT-images are obtained. Images like those depicted in Figure 3 are to be delivered to a computer that is responsible for 3D model reconstruction. Normally, these images come in the proprietary data formats and have to be converted in one of the common image formats. In our case, for all these purposes, we used SGI workstations though it could be virtually any *Unix* workstation or *Linux* computer. The choice of SGI workstation was done simply because we planned to use the 3D

reconstruction software that was available on it. Actually, the same processes could be implemented entirely on the personal computer.

After the CT images are copied to the workstation, there are basically two ways to work with them.

First, they can be automatically processed by the special software that reconstructs 3D models from the 2D slices. For these purposes, we used the free-ware software *NUAGES* by Bernhard Geiger [18] that creates 3D polygonal meshes from the 2D



contours.

Figure 3: Example of CT-images.

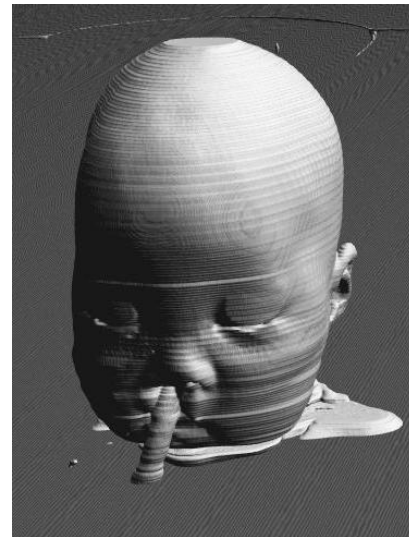


Figure 4: A 3D reconstruction from the images.

Second, for the editing purposes, we developed an interactive 3D tool that builds and edits contour lines for the CT slices and converts them to the data file later processed by *NUAGES*. In Figure 4, an example of the 3D reconstruction from the data in Figure 3 is depicted. In Figs. 5 and 6, the 3D editing tool and the reconstructed models of the femur are presented. The 3D data of the bones obtained later are converted to the data format used by our program and then transferred to the personal computer.

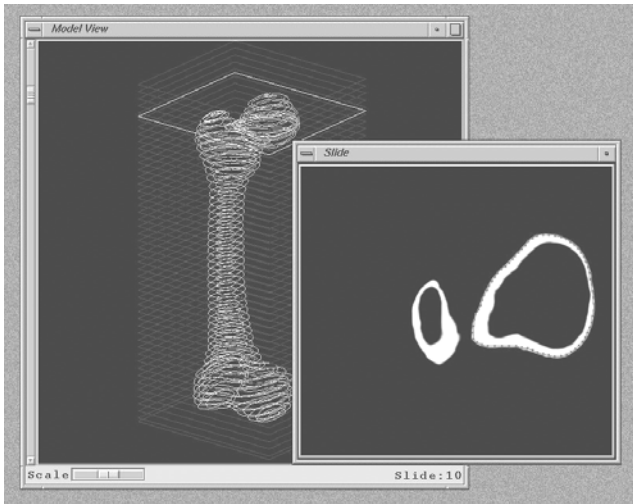


Figure 5: The interactive 3D modeling tool for extracting and editing contour lines.



Figure 6: The reconstructed femur and the femur neck.

5. OBJECTS AND OPERATIONS IN THE VIRTUAL ENVIRONMENT

Analyzing the application area, we understood that most bone fractures appear to occur in predictable patterns. For example, there are 27 types of femoral fractures (see Figure 7) and 9 types of pelvic fractures. This encouraged us to create a geometric database of the fractured bones using geometric models of the broken bones created from standardized geometric models. These bones were “broken” as needed using interactive modeling tools and other methods.

To fix fractures, surgeons use hundreds of different screws, plates, nails, wires, and locking bolts. Their geometric models and the models of the tools were also created and stored in the respective geometric databases (see Figure 8).

Since the software had to be implemented on a common personal computer, we had to find a reasonable balance between the processing time, the size, and the complexity of the model. Analyzing the goals that must be achieved, probably the straightforward method can be to implement something like the functionally based spatial spline [19]. This spline would interpolate the bones from the scattered points, and for any trial point would answer the question whether the point is inside, outside or on the boundary of the bone. Unfortunately, all these methods, providing a general solution to practically every problem, assume very extensive use of computer memory, and will not provide the required interactivity. Thus, we decided to combine different models for different purposes in our representations.



Figure 7: Several femoral fractures from the geometric database of common fractures implemented for the project.

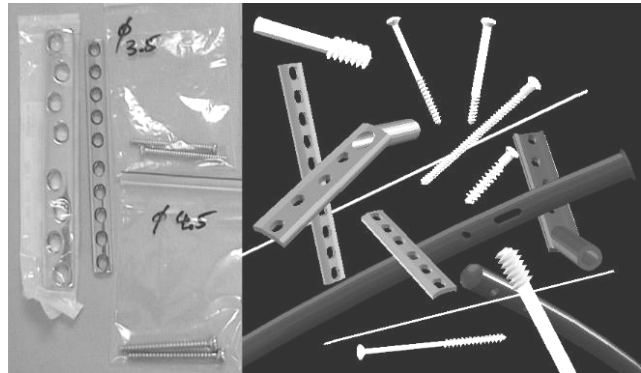


Figure 8: Real and virtual surgical tools and implants from the geometric database implemented for the project.

Internally, each geometric model in the VE is represented as a polygonal mesh with the functional description that—like geometric DNA—constitutes its shape. Extra application data is stored in the attachment to the geometric model. Thus, for example, extra information about the number, the size, and the locations of the holes for each plate are stored with the polygonal mesh and functional description of the plate. For the bones, the essential information is the location of their medial axes.

Since the final assembly somewhat resembles complex objects in CAD, each object in the VE and the scenes composed from the objects are stored in the hierarchical geometric database. For example, each plate with holes is a hierarchy of the solid plate body as a root object with the addressable holes as its children nodes. When inserting a screw through the plate, first the surgeon picks up the hole, then the inserted screw becomes yet another child node of this assembly. If the guide wire is inserted through the plate’s hole, later it will be used for inserting the cannulated screw. In that case, the coordinate systems of the guide wire and the cannulated screw will be aligned to provide the guiding effect. After the insertion, the guide wire will be removed from the scene, and the screw will substitute for it in the hierarchy.

Many common surgical techniques handle internal fixation of bone fractures, such as fixation with cancellous screws [20], fixation with an intra-medullary nail [21], dynamic condylar screw (DCS) implant system technique [22], dynamic hip screw (DHS) implant system technique [23], and so on. Analyzing them systematically from a geometric point of view, we managed to find common and specific parts that let us come up with the generic virtual fixation techniques that became foundation virtual

methods in our project. These methods have been implemented on the internal level, while the surgeon sees the familiar names and commands at the user interface.

6. COLLISION DETECTION

All the geometric and nongeometric data are used together for pseudo-physical collision detection—crucial for VR modeling. Each particular operation required developing its own respective methods and models.

For example, when inserting a screw into bone through a plate's hole, the proximity sensors of each plate implemented as functional fields engage to attract the screw tip to the nearest hole. Then, depending on the mode selected, the screw will either automatically align with the hole axis or the surgeon will have a limited ability to change its orientation, thus simulating the actual insertion of a screw. The screw being inserted never goes through the solid parts of the plate. Since the length of each screw and all the sizes of the plate are among the parameters stored in the geometric database, the screw never penetrates deeper than it should. For the surgeon, the result looks very realistic.

Another example of handling collision detection involves an implementation of nail insertion in the femoral canal (Figure 9a). The femur with its canal has a curvature of a certain radius. The nail to be inserted (Figure 9b) is a piece of a large torus with the same curvature as that of the femur.

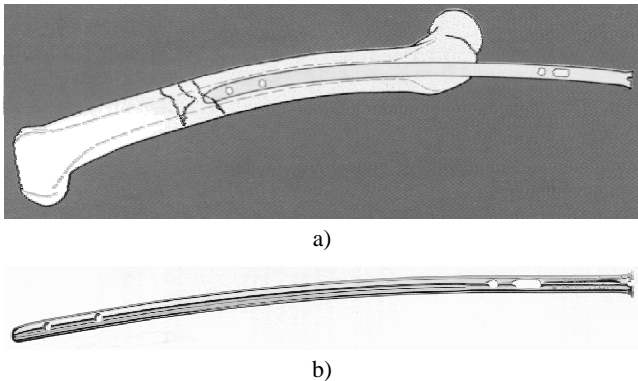


Figure 9: Universal femoral nail.

Mathematically, the problem of insertion is to find the initial location of the torus so that it lies in the same plane with the bone's medial axis and so that its axis is coincident with the axis of the bone curvature. From the surgeon's point of view, the skill required in this operation is to find the proper point and angle of insertion for the nail. These initial parameters let us solve the geometric problem of the axes' coincidence and answer the question whether in principle the nail goes freely all the way through the canal or seriously damages the bone.

These are just two examples of the methods used to solve collision detection problems in our project. Each particular operation required developing its own respective methods and techniques.

7. VIRTUAL BONE-SETTER

We called the software implemented in this project Virtual Bone-setter. The program runs on PCs with the most common architecture though the following features are preferred:

- Powerful CPU not less than 150 MHz.
- Extended RAM 64MB or above.
- Video card supporting 3D polygon rendering and real transparency.

Using a mouse as an input device controlling object relocations may suffice, but for some users it might not be as realistic as expected. Better immersion results from using relatively cheap 3D mice or graphics pads instead. The software is implemented with Criterion's Renderware, which provides the required interactivity with a reasonable quality of rendering. Comparing with the *de facto* standard OpenGL, it provides better speed of rendering though slightly sacrificing the rendering quality since it uses less number of bits for representing the colors. The ability of Renderware to model in hierarchical coordinate systems and its support of many VR devices provides a very natural environment for the geometric modeling in the project.

Starting the virtual surgery, the surgeon locates the fractured bone in 3D space looking at the screen. Then, depending on the fracture, the surgeon can issue the following basic commands:

- Applying the instruments and putting the implants in place.

To simulate the surgical techniques, the following explicit and implicit commands are used: "Insert threaded guide wire", "Insert pin", "Remove threaded guide wire", "Remove pin", "Insert multiple guide wires", "Measure for the screw length", "Insert screw", "Seat plate", "Insert nail", etc. These operations are applied to the current objects in the scene. The user is required to locate the application point on the bone, to define the orientation or to follow the guided orientation, and to apply or to insert the instrument or implant to the proper depth. In common training where expensive non-reusable synthetic bones are operated, it usually takes hours of practicing to achieve the required skills. All the models were created with the maximum possible realism to train the surgeons visually so that they will remember how all this hardware looks before they enter the training lab. Collision detection is implemented to ensure proper insertion of the implants (e.g., for the screws being inserted through the plate holes and for the cannulated screws being inserted by the guiding wires). The screws rotate about their axes when inserted. The speed of insertion slows down when the tension is growing. Drilling and cracking sounds are played for the realistic audio feedback.

- Moving, rotating, and zooming the scene and the objects in the scene.

The whole scene or individual objects can be moved, rotated or zoomed in any direction.

- Looking at the assembly through the X-ray lens.

The surgeon often inserts the wires, nails or pins to the appropriate depth under image intensification (X-ray). In the virtual environment, it is provided either for the whole scene or for the particular part of it through the so-called X-ray lens.

- Walking through the bone canal.

It allows the surgeon to look at the seated implants from inside the bone. This effect can not be achieved during the real surgery and is implemented here for education and control purposes.

- Reversing process.

If something has been done wrong, the multilevel undo operation can be applied without any damage to the models.

- Setting the lights and the background.

Different type of lights can be applied for better illumination of the surgical field thus simulating the actual environment in the operation theatre. These can be omni-directional or spot-lights.

The program guides the surgeon through the whole surgery, although the surgeon retains the ability to make independent decisions. Pseudo-physical collision detection is implemented. Realistic sounds play when the instruments are used. The scene with the fracture being fixed can be saved at any time and stored in the hierarchical geometric database for further use. If the surgeon requires an implant not in the database, its model can be created interactively and used immediately. If the surgeon wishes to study a real fracture rather than those stored in the fracture database, its geometric model can be reconstructed from CT data.

8. EXAMPLES OF VIRTUAL FRACTURE FIXATION

Femoral neck fracture fixation with cancellous screws, as depicted in Figure 10, requires the following actions:

1. The first step includes guide wire insertion to the appropriate depth. The surgeon chooses “Insert threaded guide wire ”and locates the point of insertion on the bone. The wire appears on the screen touching the bone at the selected point. The surgeon rotates the wire to the proper insertion angle and inserts it. The result of the insertion can be checked with the simulated X-ray imaging.
2. The next step is placing multiple parallel guide wires at various distances from the first wire. The surgeon selects “Place multiple guide wires ”and defines the respective points on the bone. Wires are inserted automatically parallel to the first one, thus implementing the adjustable parallel wire guide device.
3. Then, the surgeon measures for the screw length. The reading indicates the appropriate screw length. It simulates the result of applying the cannulated screw-measuring device.
4. Next comes inserting the screws. The surgeon selects the cannulated screw of the appropriate length from the database, picks up the wire, and places the screw over the wire. After that, other cannulated screws are placed over the respective wires.
5. The last step is to remove and discard the guide wires.

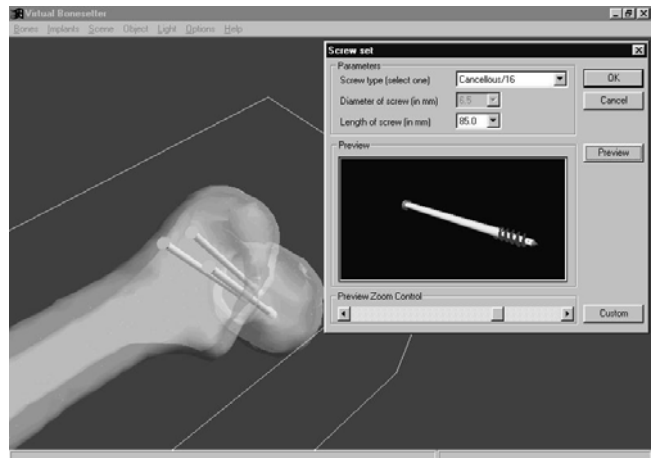


Figure 10: Virtual femoral neck fracture fixation with cancellous screws.

Another example is the inter-trochanteric fracture fixed with a DHS implant system (see Figure 11). In this case, the surgeon inserts the guide wire first, next the guide pin, and then removes the wire. The surgeon measures the pin for a screw length and inserts the DHS screw with the appropriate length over the pin. After that, the surgeon seats the appropriate DHS plate over the screw, removes the pin, and fixes the plate with cortex screws through the plate holes. Finally, the surgeon applies the DHS compressing screw to secure the assembly.

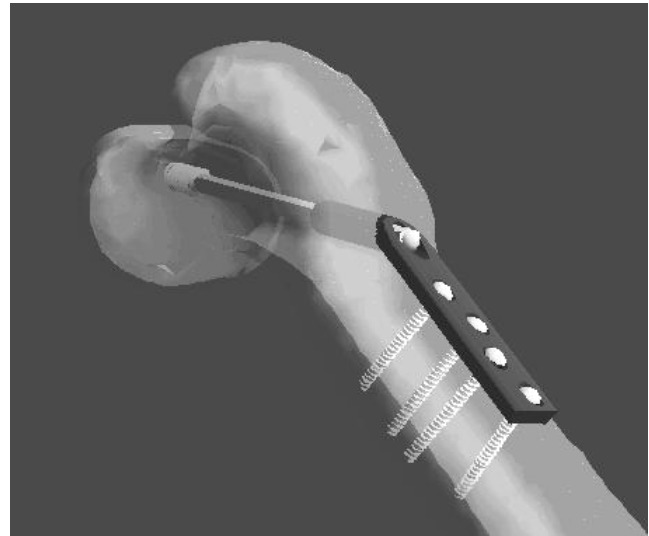


Figure 11: Virtual femoral neck fracture fixation with cancellous screws.

Yet another example of the virtual femoral fracture fixation with an intra-medullary nail appears in Figure 12. This VR surgery simulates the real surgery illustrated by the x-rays in Figure 2 and by the diagram in Figure 9a. Here, the nail—in fact, a piece of a torus—is to be inserted in the bone canal and then fixed with the screws. This operation requires hours of training before the surgeon learns exactly where to insert the nail and what the insertion angle should be.

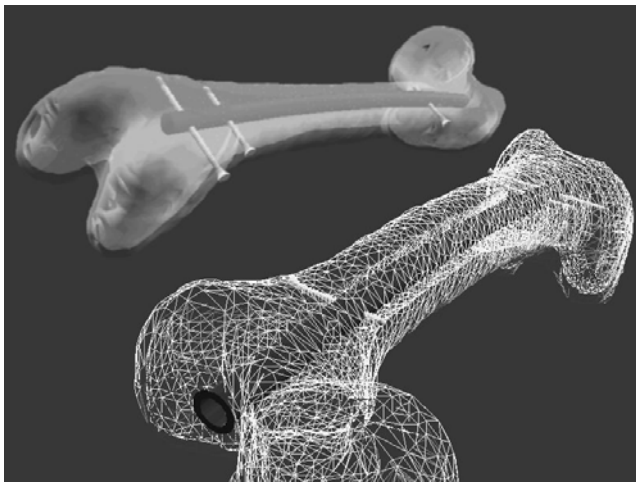


Figure 12: Virtual femoral fracture fixation with an intramedullary nail.

9. CONCLUSION

The implemented tools let surgeons learn how to fix fractured bones and perform preoperative planning without wasting expensive synthetic bones. The software works on common PCs and simulates surgical techniques, implants, and tools. Using more sophisticated virtual input/output devices, although not compulsory, increases realism and provides better immersion. Besides that, our software also may be used for simulating internal operations for some bone diseases, like slipped capital femoral epiphyses, ankle arthrodeses, sacroiliac joint disruptions, subtalar arthrodeses, and so forth.

The long-term goals of the project follow:

- Photorealistic representation of the operating room environment.
- Force feedback and tactile response using VR haptic devices.
- Object-management at different levels-of-detail.
- Greater immersion, letting the surgeon study and manipulate virtual objects on the screen or on a virtual workbench with a higher degree of realism.

These goals assume software development in both directions—on PCs and advanced software implemented on a virtual workbench. Both lines of software will use the same models and data format, allowing surgeons to handle simple cases on their home or office computers and to ring the most important or complex cases to expensive graphics workstations.

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