# 1 Virtual Bone Surgery

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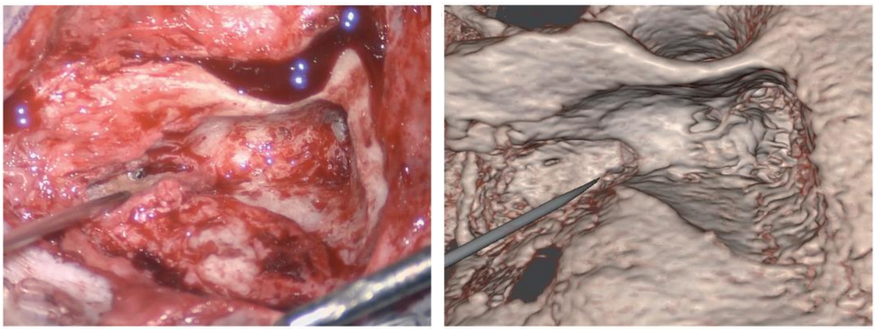
## 1.1 INTRODUCTION

To become a skillful surgeon requires rigorous training and iterative practice. Traditional training and learning methods for surgeons are based on the Halstedian apprenticeship model, i.e., “see one, do one, teach one”, which is more than 100 years old (Haluck et al., 2000). For bone surgery, students often watch and perform operations on cadaveric or synthetic bones under the tutelage of an experienced physician before performing the procedure on patients under expert supervision. In the learning process they need to learn how to perform material removal operations including drilling, broaching, sawing, reaming, and milling, etc., which simulate real operations as shown in Figure 1. Mistakes can lead to irreparable defects to the bone and surrounding soft tissue during these procedures, which can result in complications such as early loosening, mal-alignment, dislocation, altered gait and leg length discrepancy (Conditt et al., 2003). The current system of surgery education has many challenges in terms of flexibility, efficiency, cost and safety. In addition, as new types of operations are developed rapidly, more efficient methods of surgical skill education are needed for practicing surgeons (Gorman et al., 2000).

Virtual Reality (VR) is one of the most active research areas in computer simulation. Virtual reality systems use computers to create virtual environments to simulate real-world scenarios. Special devices such as head-mounted displays, haptic devices, and data gloves are used for interacting with virtual environments to provide realistic feedback to the user. The most important contributing factor to VR development has been the arrival of low-cost, industry-standard multimedia computers and high-performance graphics hardware. VR has been integrated into many aspects of the modern society such as engineering, architecture, entertainment, etc.



**(a)** **(b)**

**Fig. 1 Comparison of (a) actual and (b) virtual surgical operations (Chan et al., 2016)**

The concept of developing and integrating computer-based simulation and training aids for surgery training begins with VR simulators. VR techniques provide a realistic, safe, and controllable environment for novice surgeons to practice surgical operations, allowing them to make mistakes without serious consequences. It promises to change the world of surgical training and practice. With a VR simulator, novice surgeons can practice and perfect their skills on simulated human models, and experienced surgeons will be able to use the simulator to plan surgical procedures. VR training also offers the possibility of providing a standardized performance evaluation for the trainees.

Bone surgery is one of the medical applications which can be simulated using VR technology. There exist some surgical simulation tools for orthopedic applications such as knee surgery, but most of them involve only soft tissues. Few have considered the simulation of cutting, sawing, burring, etc., which involve operating on bones as well as on ligaments and muscles. The development of a virtual bone surgery system is very desirable for training surgeons, allowing them to visualize surgical operations such as drilling and cutting through the bone with the added realistic sense of touch during the process. As the Minimally Invasive Surgery (MIS) becomes more prevalent in orthopedics in the future, VR technology will become more and more valuable for assisting actual surgical operations. As surgical techniques are developed to reduce access to the surgical site (via smaller incisions), and instruments and implants are miniaturized to accommodate for these techniques, surgical dexterity and bone preparation and implant positioning will become a less and less forgiving part of the operation. It will be necessary to integrate VR models with images obtained during the surgical operations, the so-called Augmented Reality (AR) technology, in order to assist the surgeons in performing the MIS process.

This book chapter reviews the current virtual bone surgery systems developed in various research laboratories and discusses the basic methods and techniques used to develop these systems.

## 1.2 STATE-OF-THE-ART IN BONE SURGERY SIMULATION

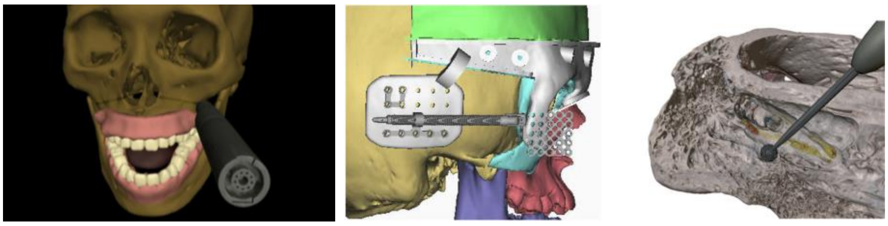
### 1.2.1 Current State of Surgical Simulation

Surgical simulation is not a newly-emerging field, and some early efforts can be found back in the 90s. It has been intensively studied for decades, which had explored a wide range of surgical operations, such as endoscopic sinus surgery (Edmond et al., 1997), tissue cutting (Delp et al., 1997), kidney removal surgery (Bro-Nielsen et al., 1998), venipuncture (Barker, 1999), wound suturing (Berkley et al., 1999), coronary anastomosis (Røtnes et al., 2002), temporal bone surgery (Wiet et al., 2000; Bryan et al., 2001; Agus et al., 2002; Morris et al., 2004), and petrous bone surgery (John et al., 2001; Jackson et al., 2002; Pflesser et al., 2002; Petersik et al., 2002).

Although surgical simulation has been studied for over 20 years, it is still an active research area as the development of virtual simulation technologies. Some recent typical studies are briefly reviewed as follows.

Lin et al. (2014) developed a surgical training simulator with both visual and haptic feedback for the user to learn the skills of bone-sawing operation (i.e., operating at an appropriate feed velocity with a suitable force) in maxillofacial surgery. The voxel-based maxillofacial model was created based on CT scanning data, and the virtual tools were modeled through reverse engineering; see Figure 2(a). Multipoint collision detection algorithms were utilized to simulate the tool-bone interaction. Similarly, Gray et al. (2017) applied pre-operative virtual surgical simulation to pediatric craniofacial surgeries, allowing for safe and precise craniofacial reconstruction in complex pediatric cases with a reduction of operative time (see Figure 2(b)).

Chan et al. (2016) described the design of a virtual surgical environment for patient-specific simulation of temporal bone surgery using pre-operative medical data. Six-degree-of-freedom haptic feedback was provided during manipulation to convey both force and torque feedback. The virtual bone dissection was modeled and simulated based on the mechanical principles of orthogonal cutting and abrasive wear. A volume rendering engine based on the technique of ray casting was developed to provide high-fidelity visual interface during the surgical manipulation of virtual anatomy (see Figure 2(c)).



**(a)** **(b)** **(c)**

**Fig. 2 Some examples of surgical simulation: (a) Lin et al. (2014); (b) Gray et al. (2017); (c) Chan et al. (2016)**

In the above virtual surgical simulators and some recent studies (Arora et al., 2014; Fang et al., 2014), most of the researchers focused on temporal bone surgery. Only a small portion of temporal bone was used in the simulation, the data was not huge, and tool-bone interaction was limited to burring/milling. In a real orthopedic surgery, however, there are also other machining operations like drilling, broaching, sawing, reaming, and milling. These operations are often needed prior to an orthopedic operation, such as pin or screw insertion to the bone. To accomplish these tasks, a virtual bone surgery system was developed at Missouri S&T. The various system components were integrated in a Windows GUI environment for purpose of implementation. The system development involved medical image processing, geometric modeling and data manipulation, force modeling, graphics rendering, and haptic rendering (Peng et al., 2003; Chi et al., 2004, 2005; Niu et al., 2005; Niu, 2008). Some of the simulated operators are shown in Figure 3.

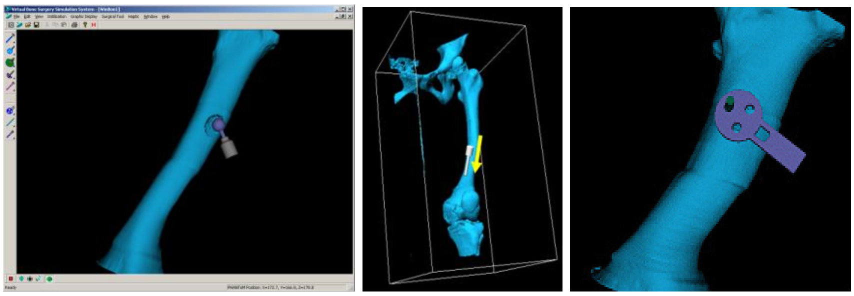


**Fig. 3 Virtual bone burring, free drilling and guided drilling (Chi et al., 2005; Niu et al., 2005)**

The simulation of material removal for bone surgery, such as drilling or milling, can be achieved similar to the simulation of a virtual sculpting process for creating a 3D freeform object from a CAD model. It should be noted, however, that bone surgery simulation deals with inhomogeneous materials while virtual sculpting deals with homogeneous materials. The material removal process can be simulated by continuously performing Boolean subtraction of the tool model from the bone model. Galyean and Hughes (1991) introduced the concept of voxel-based sculpting as a method of creating freefrom 3D shapes by interactively editing a model represented in a voxel raster. Wang and Kaufman (1995) presented a similar sculpting system with carving and sawing tools. In order to achieve real-time interaction, their system reduced the operations between the tool and the object to voxel-by-voxel operations. Gibson et al. (1997) used a volumetric approach to model organs and presented some early results of their effort to develop an arthroscopic knee surgery simulator. Computers were still too slow to allow realistic deformation of a volumetric representation at that time. Bæentzen (1998) proposed octree-based volume sculpting and discussed the possibility of using it to support multi-resolution sculpting.

To further enhance the realism of the surgical simulation, auditory feedback can be provided to augment the visual and haptic interfaces in the virtual environment. For example, the drilling sound can help operators perceive and maintain specific drilling speed and force during a surgical operation. Auditory feedback was absent in most of the previous studies, but some researchers (Wiet et al., 2002; Morris et al., 2006; Niu, 2008; Zhao et al., 2010) have explored including acoustic feedback in their vitual surgical simulators.

To realize remote surgical collaborations among surgeons or online instructions between mentors and mentees in a virtual environment, network-based multiuser surgical simulators have been investigated in some studies (Cecil et al., 2013; Cecil et al., 2014; Cecil et al., 2017; Shenai et al., 2014). In such systems, the virtual environment is shared across multiple remotely located participants to allow them to visualize and interact with the shared digital contents. The virtual contexts and multiuser interactions need to be synchronized at a high refresh rate to realize collaborations or instructions in real time.

There are some virtual surgical systems commercially available in the market. Voxel-Man has developed surgery and training simulators for medical education, possessing a series of functionalities for importing models from CT, ear surgery, endoscopic sinus surgery, and dental training. The Voxel-Man ENT simulator has been used by many researchers and proved to be effective for improving the surgical skills (Arora et al., 2014; Arora et al. 2015; Varoquier et al., 2017). Another commercial simulator for temporal bone surgery is the Mediseus Surgical Drilling Simulator, which was initially developed at the University of Melbourne. This simulator offers a VR environment with haptic feedback and manually segmented CT rendering. Distinct from other simulators, it is designed with a microscope-like interface with a stand-alone, mobile platform. This platform has been assessed and validated (Zhao et al., 2010; Zhao et al., 2011; Piromchai et al., 2014), showing the participants trained on this simulator performed significantly better than the participants trained using the conventional methods. Another alternative temporal bone simulator is the Visible Ear Simulator (VES) (Sorensen et al., 2009), which is an academic freeware platform for the training of novice and experienced ear surgeons. It is a fully functional 3-D simulator for temporal bone drilling with force feedback and photo-realistic graphics. Comparison and discussion of different VR surgical simulators can be found in the surveys by Sethia et al. (2015) and Bhutta et al. (2016).

### 1.2.2 Key Technologies

The schematic of a virtual bone surgery system is shown in Figure 4. The user can use a personal computer based system to manipulate the interaction between the virtual bone and the virtual surgical tool, and perform virtual bone surgery by “seeing” bone material removal through a graphic display, “feeling” the machining force via a haptic device, and “hearing” the sound of tool-bone interaction.

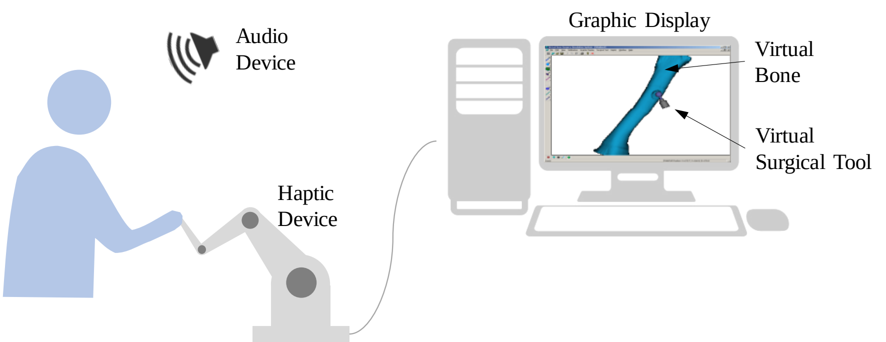



**Fig. 4 Schematic of a basic bone surgery simulation system**

Generally speaking, virtual bone surgery includes the following key elements: image acquisition and processing, geometric modeling, physical modeling, visualization, and haptic interaction. The relationships between these key elements are illustrated in Figure 5. Usually, image acquisition and processing precedes the simulation and it is done off-line in order to save the data processing time during the online simulation.

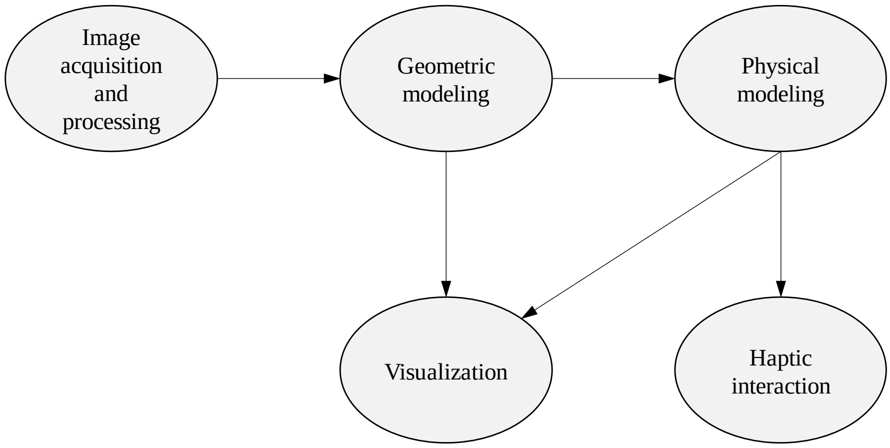



**Fig. 5 Key elements involved in bone surgery simulation**

A virtual bone surgery system consists of the following main elements (Figure 5):

1. Input the CT or MRI data of the bones to construct a geometric model with properties such as materials and densities.
2. Develop mathematical models to represent the physics of tool-bone interaction, based on which the interactive force and sound generation are updated continuously (e.g., to simulate the drilling of a bone).
3. Implement real-time graphic rendering of volumetric data to obtain realistic visualization of bone surgery.
4. Provide force feedback to the user with haptic rendering.
5. Supply sound feedback to the user with auditory rendering.

To develop a meaningful virtual bone surgery system with realistic visual effects, force feedback, and auditory rendering, several requirements that must be met are:

1. The medical data obtained from image acquisition must be processed to minimize noise and irrelevant data (Jackson et al., 2002; Niu et al., 2005). This data processing must be done before bone surgery simulation.

2. The virtual surgery system must update various data at different frequencies: above 30 Hz for visual rendering and above 1,000 Hz for haptic rendering (Mark et al., 1996). For the system including auditory rendering, besides the visual and haptic rendering, 20k Hz is the required frequency to update the collision checking flag and send the calculated sound signal to auditory hardware (Niu 2008).
3. Data modification calculation should involve only local data to reduce augmentation time (Avila and Sobierajski, 1996; Astley et al., 2000).
4. The amount of force computation time should be small for real-time haptic readering (Avila and Sobierajski, 1996).

## 1.3 MEDICAL IMAGE PROCESSING AND SEGMENTATION

### 1.3.1 Imaging Procedures

Computer imaging techniques have become an important diagnostic tool in the practice of modern medicine. Today, advanced medical scanners can provide high-quality and exceptionally detailed images for surgeons before performing the actual surgical procedures. Medical data obtained from imaging techniques typically represent the values of some properties at various 3D locations (Kaufman et al., 1993). The most commonly used medical imaging techniques include CT (Computed Tomography), MRI (Magnetic Resonance Imaging), SPECT (Single-Photon Emission Computed Tomography) and PET (Positron Emission Tomography), as shown in Figure 6. These techniques use a data acquisition process to capture information about the internal anatomy of a patient. This information is in the form of slice-plane images, similar to conventional photographic X-rays (Schroeder et al., 2002).

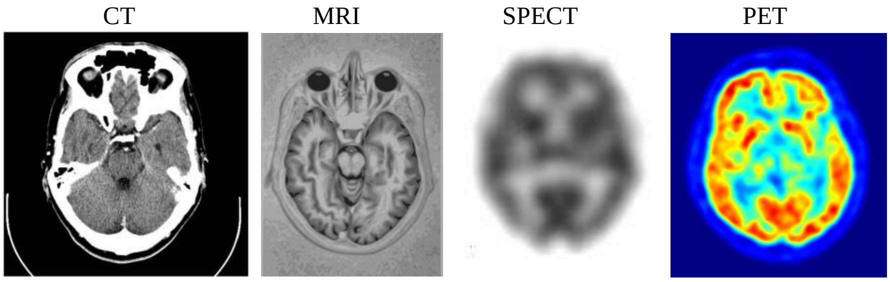



**Fig. 6 The most commonly used medical imaging techniques (Photos from Wikipedia)**

CT and MRI are most commonly employed in obtaining medical images. CT provides high spatial resolution bone images while MRI provides better images on soft tissues. For most bone surgery simulators, CT scan data are used because they show good contrast between bones and soft tissues. For reporting and displaying reconstructed CT values, Hounsfield Unit (HU) is a standardized and accepted unit. There are good correlations between CT scan data and bone's material properties such as density and mechanical strength (Bentzen, 1987), so HU value is usually used to represent bone density for each data point.

The process of constructing a VR environment from the imaging data is a major challenge. This process can be divided into three stages: 1) spatial co-registration of data from multiple modalities; 2) identification of tissue types (segmentation); and 3) definition of tissue boundaries for the VR environment (Jackson et al., 2002).

### 1.3.2 Image Processing

Noise and other artifacts are inherent in all methods of data acquisition. Due to noise in many signals and lots of irrelevant information in the medical data, image processing is necessary. Filtering and smoothing techniques, e.g., Gaussian filters and median filters, are usually used to reduce noise on images (Schroeder et al., 2002). Since information gained from two images acquired in medical imaging procedures is usually complementary, proper integration of useful data obtained from the separate images is often desired. Image registration is the process of determining the spatial transform that maps points from one image to homologous points on the same object in the second image (Luis et al., 2003). These images could have a different or the same format. The most common registration methods could be found in the survey of medical image registration by Maintz and Viergever (1998).

It is also necessary to identify which type of tissue is present in the data space and to identify the precise location of edges between different tissue types. Image segmentation is the process of identifying the distribution of different tissue types within the data set. Bones can be extracted by manual or partially automated segmentation methods. Usually, threshold segmentation is used to distinguish pixels or voxels within an image by their gray-scale values. A upper and lower threshold can be defined, separating the image into the structure of interest and background. This method works very well for bone segmentation from CT scans since bone tissue attenuated significantly more during image acquisition and is therefore represented by much higher values on the Hounsfiled scale compared to soft tissues. Whereas thresholding focuses on the difference of pixel intensities, the segmentation methods look for regions of pixels or voxels with similar intensities (Ritter et al., 2004).

Segmentation methods are usually divided into two types: region-based and edge-based (Kovacevic et al., 1999). The region-based methods search for connected regions of pixels/voxels with some similar features such as brightness, texture pattern, etc. After dividing the medical image into regions in some way, similarity among pixels is checked for each region, and then neighboring regions with similar features are merged into a bigger region, and regions with no similar features are splitting into smaller regions. These steps are repeated until there is no more splitting or merging. A main issue of this approach is to determine exact borders of objects because regions are not necessary to split on natural borders of the object. Edge-based algorithms search for pixels with high gradient values which are usually edge pixels, and then try to connect them to form a curve which represents a boundary of the object. A difficult problem here is how to connect high gradient pixels because in real images they are often not neighbors. Another problem is noise since a gradient operator is of a high-pass nature, the noise is usually also in high frequencies, and it can sometimes create false edge pixels.

## 1.4 GEOMETRIC MODELING AND DATA MANIPULATION

### 1.4.1 Volume Modeling

The sequence of 2D slices of data obtained by CT, MRI, or ultrasound can be represented as a 3D discrete regular grid of voxels (volume elements), as shown in Figure 7. For virtual surgery, voxel-based modeling has some advantages over the use of polygons or solid geometric primitives. First, voxel-based representation is natural for the 3D digital images obtained by medical scanning techniques such as MRI or CT. Second, since no surface extraction or data reformatting is required, errors introduced by fitting surfaces or geometric primitives to the scanned images can be avoided. Third, volumetric objects can incorporate detailed information about the internal anatomical or physiological structure of organs and tissues. This information is particularly important for realistic modeling and visualization of complex tissues (Gibson et al., 1997).

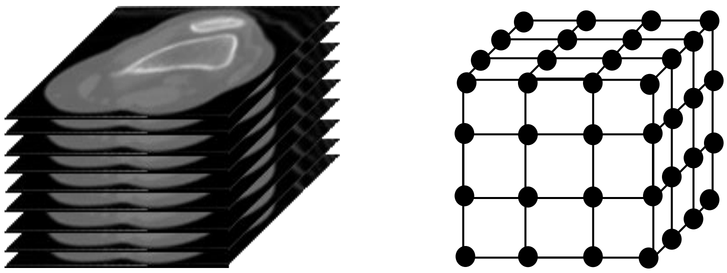


**Fig. 7 A volume seen as a stack of images and a volume seen as a 3D lattice of voxels**

In volume representation, the basic elements are voxels (Bærentzen, 2001). Just as a pixel is a small rectangle, a voxel can be viewed as a small block. A voxel can be represented by the coordinates of its center point and the three orthogonal dimensions plus some attributes. If the voxels have fixed dimensions, then they can be represented by the vertices of a 3-D lattice, which are characterized by their positions and associated values of attributes. For example, it can be expressed as an array ($x, y, z, v_1, v_2, \ldots v_n$), where ($x, y, z$) represents the position of each voxel and $v_i$ represents a property. These physical properties can be density, material classification, stiffness, and viscosity as well as display properties such as color, shading, etc.

In general, the samples may be taken at random locations. Depending on how the samples are connected to form a grid structure, there are two classes of volumetric data: structured and unstructured. Structured data have two components: a logical organization of the samples into a three-dimensional array, and a mapping of each sample to the physical domain. Unstructured data are a set of connected samples in space. They are not based upon a logical organization of arrays, but instead upon a group of cells of certain shapes, such as tetrahedra, hexahedra, or prisms.

An interpolation function is used to produce a continuous scalar field for each property. This is critical for producing smooth volume and haptic rendering (Avila and Sobierajski, 1996). In order to meet the system requirements, it is often desirable to pre-compute and store the contents of each voxel, so there is no need to change every voxel during the surgical operation simulation. By storing the volumetric data in a space-efficient, hierarchical structure such as an octree, the storage requirements can be reduced.

### 1.4.2 Data Manipulation

The data set for virtual surgery is usually huge. For example, for a medium resolution of $512^3$, two bytes per voxel, the volume buffer must have 256M bytes (Kaufman et al., 1993). Therefore, how to organize and manipulate such huge data is a challenging problem.

Zhu et al. (1998) used a finite element method (FEM) in their analysis of muscle deformation. A muscle was modeled with 8-node, 3D brick elements equivalent to the voxel structure. The simulation was achieved by solving a sparse linear system of equations which governs the behavior of the muscle. Like most other FEM models, computation is costly and pre-computation is often required for real-time applications. Gibson et al. (1996) developed a linked volume model to represent the volumetric data. The links were stretched, contracted or sheared during object deformation, and they were deleted or created when objects were cut or joined. Compared with the FEM method, the linked volume approach can be used for creating models with high geometric complexity, and it could achieve interactivity with the use of low-cost mathematical modeling.

Bæentzen (1998) proposed an octree-based volume sculpting method in order to quickly separate many homogeneously empty regions outside the object of interest. An octree structure as shown in Figure 8 was chosen to organize the huge set of volumetric data and to improve the efficiency for data storage. A volume was subdivided until the leaf level of a prescribed size had been reached. It will significantly reduce the memory requirement and speed up the graphics rendering and modeling task. Basically, octrees are a hierarchical variant of spatial-occupancy enumeration that can be used to address the demanding storage requirements in volume modeling (Foley et al., 1996).

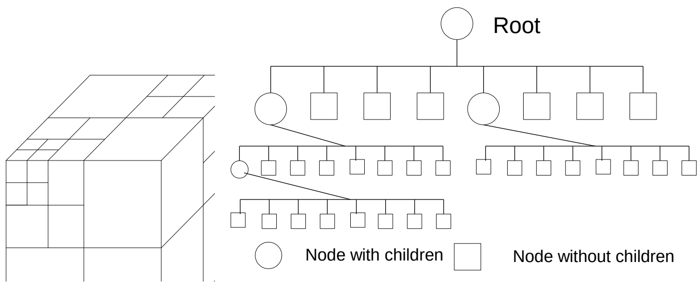
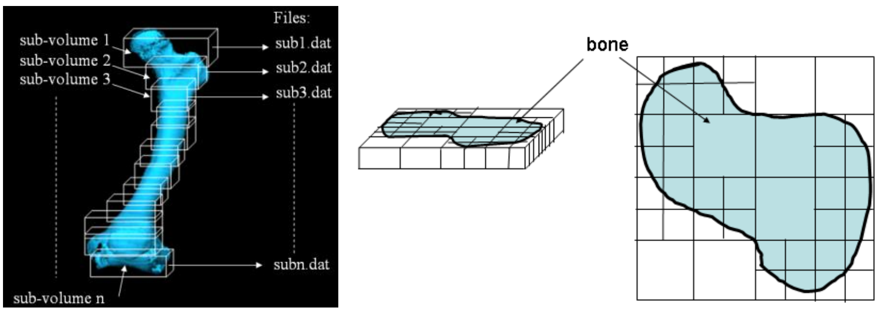



**Fig. 8. Octree representation**

In virtual bone surgery, operation tools such as drills, mills, and broaches remove voxels occupied by the cutting tool's volume during the course of the machining operation. For static data structure, e.g., 3D arrays, voxels can only be removed in the defined size. That is, the cells representing the interaction between the cutting tool and the bone are constant in size, and thus the resolution is static. Due to this limitation, voxel removal can only be done on a rough level. Octree modeling can provide a flexible data structure for performing material removal simulation dynamically. High resolution can be achieved in the region of interest, which is usually the current surgical tool location and its neighborhood. The octree nodes representing cells in the region of interest are subdivided to generate children nodes representing sub-cells. The material removal operation is then done on the children node level. The subdivision process can be repeated until the desired resolution is reached. To control the resolution automatically, a criterion to end the subdivision can be set. For example, one criterion could be that the smallest linear dimension of the voxel is equal to the radius of the drill or mill multiplied by a factor.

Another method is using Bounding Volume together with Quadtree Subdivision (Niu et al., 2005) to deal with irregular long bones. This method uses AABB (Axis Aligned Bounding Box) as the bounding volume type to determine a tight bounding box for the bone model. The whole of the bone volume is divided into many sub-volumes, which have certain slices/layers in the Z direction and different dimensions in X and Y directions. All these sub-volumes should have relatively tight bounding boxes around the objects as shown in Figure 9(a). Then, Quadtree subdivision is obtained by successively dividing the sub-volumes from 1 to *n* in both *x* and *y* dimensions to form quadrants as shown in Figure 9(b). Each quadrant of the sub-volumes may be full, partially filled, or empty, depending if the entity of consideration intersects the area of concern. This method has been applied to remove irrelevant data and to organize the rest data, in order to make the virtual surgery system interactive in real time (Niu et al. 2005).



(a) (b)

**Fig. 9 Bounding volume and Quadtree subdivision for human bone**

## 1.5 GRAPHIC RENDERING

Volume visualization is the technique used to display the information inside volumetric data using interactive graphics and imaging. The methods of graphic rendering of three-dimensional data (volumetric data) can be grouped into two: (1) Surface Rendering or indirect rendering and (2) Volume Rendering or direct rendering. To choose which kind of rendering method is suitable for the bone surgery system, the following considerations are important: (1) real-time rendering and (2) surface quality. Surface rendering extracts polygons from volumetric data and renders the surface interactively. It is more difficult for volume rendering to have interactive performance.

### 1.5.1 Surface Rendering

Marching Cube (Lorensen and Cline, 1987) is the most popular algorithm in surface rendering. The marching cube algorithm traverses all boundary cells of the volume and determines the triangulation within each cell based on the values of the cell vertices. This method first partitions a volume data into cubes. Each cube consists of eight voxels. Then it decides the surface configuration of each cube according to 15 configurations (Figure 10). Marching cube leads to satisfactory results for small or medium datasets. However, for simulation in the medical field, there usually exists a huge dataset which may restrict the interactive manipulation. Use of octrees for faster isosurface generation (Wilhelms and van Gelder, 1992) is an improved algorithm for extracting surfaces from volume data. This algorithm stores min/max voxel values at each octree node, and then traverses octree nodes that may contain an isosurface to obtain the triangles forming the surface. Other researchers (Shekhar et al., 1996; Sutton and Hansen, 1999; Velasco and Torres, 2001) also presented improved octree-based marching cube algorithms and their applications. The methods used some techniques to save storing space and improve performance, but none of them supported multi-resolution isosurface extraction.

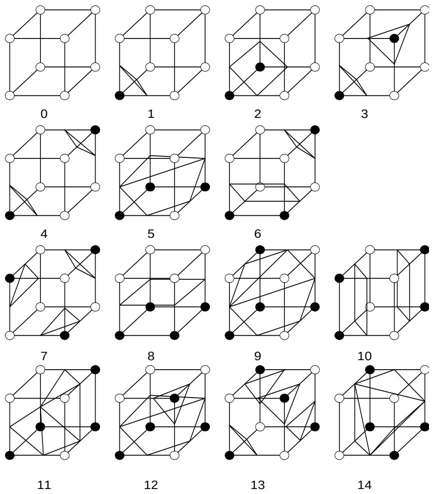



**Fig. 10 The marching cube algorithm for surface rendering of voxel data**

Adaptive-resolution surface rendering is the method mostly used for virtual bone surgery. Some researchers (Westermann et al., 1999; Boada and Navazo, 2001) presented ideas on this surface rendering method. The rendering algorithms are based on an extended marching cube algorithm for octree data as follows:

1. Find the region of interest (i.e., the current surgical tool location and its neighborhood).
2. The region of interest is rendered in high resolution, meaning that the cells are subdivided into sub-cells, and the surface is extracted on the sub-cell level using the marching cube algorithm.
3. Regions not in the region of interest are rendered in lower resolution. The cells are merged to form coarser-level cells.

Trade-off exists between surface quality and interactivity. Although octree can address this problem to some extent, interactivity is still challenging to achieve for a large set of data. In order to improve performance, the initial resolution (usually not a very fine level) for the surface rendering needs to be specified. The dynamic resolution depends on how the surgical tool interacts with the bone material. Parallel computing can be used to increase the resolution.

### 1.5.2 Volume Rendering

In this rendering method, the volume data are directly displayed, which means that the images are generated through the transformation, shading, and projection of 3D voxels into 2D pixels. Volume rendering demands greater computational processing but produces images with greater versatility. Since all the voxels located in the line of view are used in the image generation, this method allows the visualization of parts inside the surface. Although real-time rendering can hardly be achieved, this method is a good choice for applications with some special visualization requirements. Volume rendering will become more attractive in the future as computers are becoming faster and cheaper with larger memory.

The most popular algorithm of volume rendering is *Ray-Casting* (Levoy, 1988 and 1990). Traditionally, the ray-casting algorithm spans the projection plane and casts the rays into the scene. Usually, parallel rays orthogonal to the projection plane are cast. These rays are cast from the observer position to the volume data. For each ray, sample points are calculated considering a fixed step on the path traced by the ray. The algorithm can calculate and accumulate both color and opacity values along the ray for obtaining the pixel color. Besides ray-casting, there are other popular algorithms in the volume rendering approach, e.g., splatting (Westover, 1990), shear-warp (Lacroute and Levoy, 1994), and 3D texture-mapping (Cabral et al., 1994). Meißner (2000) did an extensive survey on these various volume rendering algorithms.

Currently, most bone surgery simulation systems do not use volume rendering because of the interactivity restriction, the need for expensive dedicated graphics hardware for this rendering method, and the need for huge amounts of computation time and substantial amounts of storage space. However, the merits of volume rendering along with the continuing decrease in computation costs may compel the researchers to use this method in the future.

## 1. 6 HAPTIC RENDERING

Haptic interface can enhance the realism of virtual surgery by providing a realistic feel of the surgical operation. Haptic rendering is the process of applying reactive forces to the user through a force-feedback device (Okamura, 1998). The rendering consists of using information about the tool-object interface to determine forces to be displayed, given the action of the operational point. The major challenge in simulating force-reflecting volume models is to achieve an optimal balance between the complexity of geometric models and the realism of the visual and haptic displays in real-time.

The following issues must be addressed in order to provide meaningful force feedback(Peng et al., 2003; Hua and Qin, 2002):

1. Force computation rate: This rate must be high enough and the latency must be low enough to generate a proper feel of the operation.
2. Generation of contact force: This creates the feel of the object during the surgical simulation. Interaction forces between the tool and the bone can be calculated using mathematical models.

For haptic rendering, there are several important components: force modeling, collision detection, and haptic rendering as shown in Figure 11.

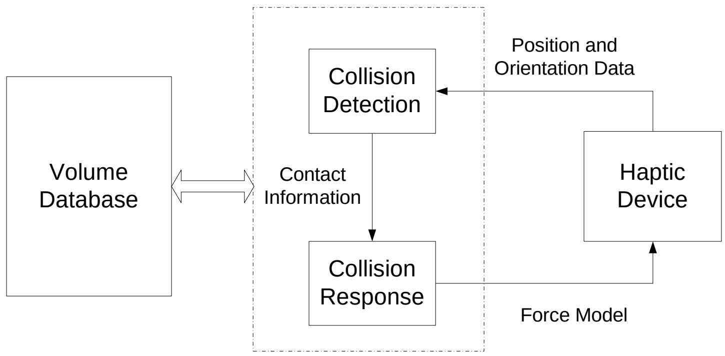



**Fig. 11 Structure of haptic rendering**

### 1.6.1 Force Modeling

Bone material removal operations are of considerable importance in orthopedic surgery (Plaskos et al., 2003). In hip and knee replacement procedures, for instance, the geometrical accuracy of the prepared bone surface is particularly relevant to achieving accurate placement and good fixation of the implant.

Bone drilling is needed prior to many orthopedic operations, such as pin or screw insertion to the bone, and it requires high surgery skills. There were several studies on bone drilling reported in the literature. Wiggins and Malkin (1976) investigated the interrelationships between thrust pressure, feed rate, torque, and specific cutting energy (energy per unit volume required to remove material) for three types of drill bits. Jacob et al. (1976) presented research results showing that the drill point geometry was critical when attempting to minimize drilling forces and that a softening effect occurred when the bone was drilled at relatively high speeds. Hobkirk and Rusiniak (1977) studied the relationships between drilling speeds, operator techniques, types of drills and the applied forces in bone drilling. Through experiments they showed that the peak force exerted on the drill varied between 5.98 and 24.32 N, and that the mean vertical force ranged from 4.22 to 18.93 N. Karalis and Galanos (1982) tested the drilling force against the bone hardness and triaxial strength, and found a linear correlation between the triaxial compressive strength and the drilling force. Abouzgia and James (1995) investigated the dependence of force on drill speed and measured the energy consumption during drilling. They found that the drilling force increased slightly with increase in speed at low starting speeds and decreased with increase in speed at high starting speeds. Some machining force models proposed later by other researchers are given below with specific equations.

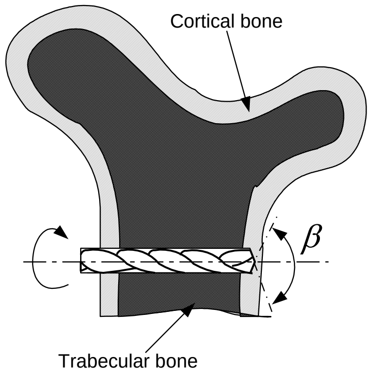



**Fig. 12 Modeling force in drilling a long bone.**

Allotta et al. (1996) developed an experimental model for the description of a breakthrough during the penetration of a twist drill in a long bone as illustrated in Fig. 12. They presented an equation for thrust force required to drill a hole and reported its good correlation with experimental data. The thrust force required to drill a bone is

$$T = K_s a \frac{D}{2} \sin\frac{\beta}{2} \tag{1}$$

where $T$ is thrust force, $K_s$ is the total energy per unit volume, $a$ is the feed rate expressed in unit length per revolution, $D$ is the diameter of the drill bit, and $\beta$ is the convex angle between the main cutting lips (see Fig. 12). $K_s$ represents the sum of shear energy required to produce gross plastic deformation. It is primarily the friction energy of the chip sliding past the tool plus other minor energies. $K_s$ has been shown to vary between $4.8R_u$ and $6R_u$, where $R_u$ is the unitary ultimate tensile load. $K_s = 5R_u$ is a practically acceptable value. During rotation and penetration across the bone, the drill bit is subject to a resistant torque (besides the thrust force) of

$$M_z = 5R_u a \frac{D^2}{8} \tag{2}$$

Udilijak et al. (2003) investigated the key parameters affecting bone drilling and modeled the force of drilling as a function of influencing parameters including axial feed, cutting speed, and drill tip angle. After experiments, they obtained the mathematical dependence of axial drilling force on the influencing parameters as follows:

$$F = 58.42 f_z^{0.439} \varepsilon^{3.024} \tag{3}$$

where $F$ is axial drilling force in N, $f_z$ is feed rate per tooth in mm, $\varepsilon$ is drill tip angle in rad.

Chi et al. (2005) presented another drilling force model by performing regression of measured drilling force versus process and material parameters. The obtained force model was validated by performing more experiments with different sets of parameter values. The thrust force model can be written as:

$$T = 134.6 N^{-0.3327} v^{0.5189} \rho^{1.1841} \tag{4}$$

where $T$ represents the thrust force, $N$ is the speed of drill bit in rotations per minute, $v$ is feed-rate in mm/sec, and $\rho$ is bone material density in g/cc.

Bone burring is also an important surgical procedure used in temporal bone surgery. Agus et al. (2002) presented a bone-burr interaction model. For a burr with a spherical bit of radius $R$ rotating at angular velocity $\omega$, they used Hertz's contact theory to derive the following elastic deformation force that exerts on the burr:

$$\vec{F}_e = C_1 R^2 \left( \frac{h}{R} \right)^{\frac{3}{2}} \hat{n} \tag{5}$$

where $C_1$ is a constant that depends on the elastic properties of material, $h$ is the tool embossing height. $\hat{n}$ is the normal direction of the contact surface. Also, the friction force can be obtained as

$$\overrightarrow{F_\mu} = \mu \int_\xi P(\vec{\xi}) \frac{\vec{r}(\vec{\xi}) \times \vec{\omega}}{|\vec{r}(\vec{\xi}) \times \vec{\omega}|} d\sigma \tag{6}$$

where $\mu$ is a friction coefficient, $\vec{\xi}$ represents a point on the contack surface, $P(\vec{\xi})$ is the pressure exerted by the burr at point $\vec{\xi}$, and $\vec{r}(\vec{\xi})$ is the displacement measured from the center of sphere burr bit to point $\vec{\xi}$, and $d\sigma$ represents a differential area on the contack surface.

The total force that should be provided by the haptic feedback device is

$$\vec{F}_T = \vec{F}_e + \vec{F}_\mu \quad (7)$$

Other force models can also be applied in developing a virtual bone surgery system. For example, Eriksson et al. (2005) used an energy-based approach to determine how the force relates to material removal rate in the milling process. This model is the same as the following simplified milling force model (Yang and Chen, 2003; Choi and Jerard, 1998):

$$F_t = K_t(MRR)/f \quad (8)$$

where $F_t$ is the tangential cutting force, $f$ is the feedrate, $MRR$ is the material removal rate. The radial cutting force is

$$F_r = K_r F_t \quad (9)$$

where $K_t$ and $K_r$ are constant and their values depend on workpiece material, cutting tool geometry, and cutting conditions.

There are other force models, e.g., the spring-damping force model (Hua and Qin, 2002; McNeely et al., 1999; Avila and Sobierajski, 1996) that could also be applied to virtual bone surgery.

A haptic device can be used to give the user of the virtual bone surgery system realistic force feedback by rendering the force and torque computed using the cutting force models. Most virtual bone surgery systems use PHANToM device (SensAble Company) and GHOST SDK for haptic rendering. Two examples of such a system are shown in Figure 13. This PHANToM has three motors and six encoders to enable 6-DOF motion tracking and 3-DOF force feedback. The GHOST (General Haptics Open Software Toolkit) SDK is a C++ object-oriented software toolkit that enables developers to interact with the haptic device and create a virtual environment at the object level. GHOST SDK provides a special class of functions called gstEffect, which allows adding “global” forces directly to the PHANToM. At each iteration of the servo loop, the pointer of the Effect object is passed to a PHANToM node. By generating the Effect force when non-null intersection between the virtual tool and the virtual bone is detected, the system gives the user a realistic feel of force in real time.

(a) (b)

**Fig. 13 Virtual bone surgical with haptic feedback: (a) Agus et al. (2002); (b) Chi et al. (2005).**

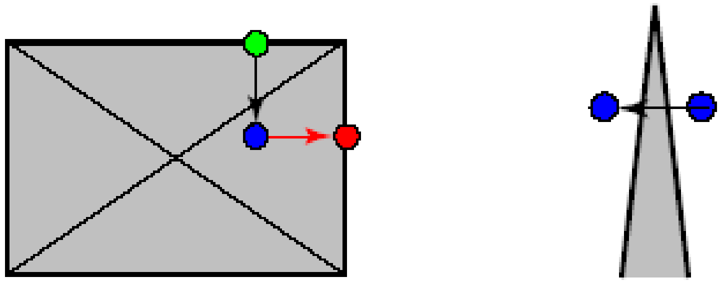
In order to run the components of a virtual bone surgery system asynchronously, a multithreading virtual environment can be implemented. The multithreading computation environment allows maintaining suitable update rates for the various components and subsystems of the simulation system. The haptic loop must maintain an update rate of above 1,000 Hz, while the graphics loop can get by with an update rate of above 30 Hz.

### 1.6.2 Collision Detection and Force Generation

In a bone surgery simulator, the haptic rendering consists of two parts: collision detection and force generation. The goal of collision detection, also known as interference detection or contact determination, is to report a geometric contact when it is about to occur or has just occurred (Lin and Gottschalk, 1998). Fast and accurate collision detection between geometric models is a fundamental issue in computer-based surgery simulation. In developing a virtual bone surgery system, it is necessary to perform collision detection for the purpose of simulating material removal and force feedback.

An early approach to haptic rendering used single-point representation of the tool for collision detection and penalty-based methods for force generation (Massie and Salisbury, 1994; Avila and Sobierajski, 1996). Collision detection was done by checking whether the point representing the tool was inside the object of consideration such as a bone. The surface information of an anatomic model can be obtained in terms of triangular facets using the marching cube algorithm previously described or by a method of surface reconstruction from dexel data (Peng et al., 2004).

Penalty-based methods generate a pre-computed force field based on the shortest distance from the interior point of an object to the object's surface. Figure 14 shows the problems of penalty based haptic rendering. One problem with this approach is that there may be points in an object which have the same distance to the surface (see Figure 14(a)). Another problem is that when pressing an object with a sharp tip or fine feature, such as the one shown in Figure 14(b), the user will quickly feel the change of force direction from one side of the object to the other side and then feel no force at all. This can be a serious problem, especially when working with highly detailed models and small structures.



(a) (b)

**Fig. 14 Problems of penalty-based haptic rendering**

Constraint-based methods were introduced by Zilles and Salisbury (1995) and by Ruspini et al. (1997, 1998). These methods use an intermediate object (representing the tool) which never penetrates a given workpiece, such as a bone in the environment, as shown in Figure 15. The intermediate object (called God-Object or Proxy) remains on the surface of the workpiece during the simulation process. The force generated by the haptic device is proportional to the vector difference between the physical position of the virtual tool and the proxy position of the virtual tool. The haptic rendering algorithm updates the proxy position in respect to the physical position by locally minimizing the distance from the proxy position to the physical position. Since these calculations have to be performed on-the-fly, constraint-based approaches are computationally more expensive than penalty-based approaches.

The single-point representation of an object for collision detection, as described above, has the following drawbacks:

1. It is not suitable for inhomogeneous workpiece material, e.g., human bone.
2. It does not represent the 3D shape of the surgical tool.
3. The virtual tool can reach points which may not be reachable by the real tool, e.g., entering a small hole with a large tool (Niu and Leu, 2007).

Multi-point collision detection methods have been developed more recently (McNeely et al., 1999; Petersik et al., 2002). These methods represent 3D shapes using multiple points on the surface of the tool. Using these methods, more realistic simulations of tools and tool-object interaction can be achieved and the drawbacks of the single-point approach can be overcome. However, multi-point collision detection is computationally more expensive. Moreover, this force feedback scheme may generate an unstable force in some cases (Nakao et al., 2003), especially when the number of points on the tool surface is not adequate.

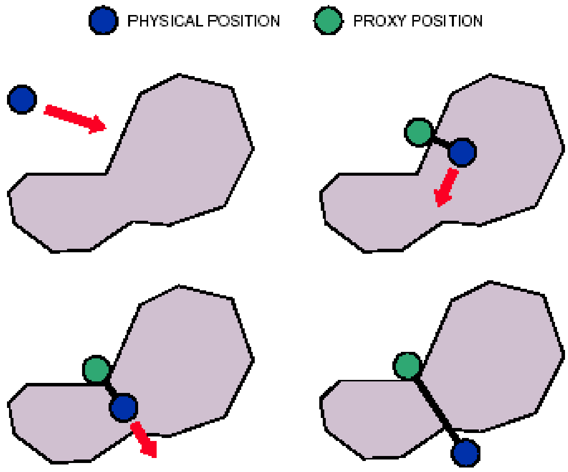



**Fig. 15 Haptic rendering by virtual proxy (Zilles and Salisbury, 1995)**

## 1.7 AUDITORY RENDERING

Sound cues can enhance haptic feedback when a user is interacting with an object in a virtual environment. In bone surgery, sound can provide information about the nature of the tool-bone contact region where the material removal operation occurs. For example, the change of sound from higher to lower pitches in bone drilling could signal reaching the interface between the bone and the soft tissues. Thus it is desirable to include auditory rending in the system development, so that the VR system can be enriched to a full multimodal interaction environment including auditory rendering, besides graphics and haptics rendering. Therefore, the user can perform virtual bone surgery by simultaneously "seeing" bone material removal through a graphics display device, "feeling" the force via a haptic device, and "hearing" the sound of tool-bone interaction.

In a virtual reality system with sound rendering, two kinds of sounds can be used: pre-recorded sound and synthesized sound. Pre-recorded sound is easy to acquire and playback. However, there are several drawbacks associated with using pre-recorded sounds (Miner and Caudell, US patent, 2004). Most importantly, the sound is static and cannot be changed in response to changes in a simulation environment including user interactions. Also, a large sound library is required to create a VR system with an acoustically rich virtual environment. Furthermore, it is difficult and impractical to obtain an application-specific sound sequence for every application. Synthesis sound, on the other hand, is flexible, dynamic, and especially advantageous for the user action related virtual reality scenarios compared to pre-recorded sound. Thus, in the virtual bone surgery system developed by Niu and Leu (2007), synthesized sounds were used to simulate the material removal process in drill-bone interaction.

Although some research work can be found in the literature regarding the synthesis of contact sound for interactive simulation in a virtual environment (Pai et al., 2001; van der Doel and Pai, 1998), there has been little effort on sound synthesis for material removal. Most studies in virtual bone surgery concentrate on graphics and haptic interfaces, and few papers (Wiet et al., 2002; Morris et al., 2006; Niu, 2008; Zhao et al., 2010) can be found in the literature about auditory rendering for virtual bone surgery. Information in these studies did not address the subtle change in sound characteristics (Shine et al., 2006). The most challenging issue of sound synthesis in virtual bone surgery is to have a sound model that allows real-time simulation while being sufficiently accurate to represent the important features of the sound during tool-bone interaction (Niu, 2008).

### 1.7.1 SOUND MODELING

There has been some initial work on sound modeling for interactive bone surgery simulation in a virtual environment. Most of these methods can be categorized into physical modeling and spectral modeling. Physical modeling employs the knowledge of the physical laws that govern the motions and interactions within the system under study and expressing them as mathematical formulae. Spectral modeling is based on modeling the properties of sound waves as they are perceived by the listener (Tolonen et al., 1998).

Besides the two main categories of sound modeling synthesis methods mentioned above, there are also some other methods like Frequency Modulation (FM) method and Auto Regressive (AR) method found in the literature. FM modeling, originally introduced by Chowning (1973), is a fundamental digital sound synthesis technique that employs an oscillating function. It combines two or more sinusoidal waves to form more complex waveforms. AR modeling was used by Kim et al. (2005) to simulate small drill sound for a dental simulator. This mathematical modeling of a time series assumes that each value of the series depends only on a weighted sum of the previous values of the same series plus noise. The linear models give rise to rapid and robust computations.

Although there are many methods of sound modeling, there has been little work on sound synthesis associated with material removal (Shine et al., 2006, Niu, 2008). It is difficult to use a physics-based method to model the machining sound because the mechanism of sound generation in the bone material removal process is highly complex.

The primary objective of sound modeling and rendering for virtual bone surgery is to generate the sound of tool-bone interaction during the bone material removal operation. Thus, the virtual bone surgery system development consists of sound acquisition in the real world, sound characteristics analysis, mathematical model generation, and sound rendering for auditory display (Niu, 2008).

Niu and Leu (2007) based on spectral modeling to develop a virtual bone surgery system. A sound model was developed and used to generate the synthetic sound in virtual bone surgery. It was modeled as the sum of a set of sinusoids plus a noise residual. Spectral Modeling Synthesis (SMS) was used for the virtual bone surgery simulation to determine the sinusoids and residual. SMS was used to find the mathematical models for free-drilling, cortical bone drilling, cancellous bone drilling, etc. The general form of SMS can be written as (Serra, 1989):

$$s(t) \approx \hat{s}(\mathrm{t}) = \sum_{k=1}^{K} A_k\, sin(\omega_k t + \theta_k) + r(t)$$

where $s(t)$ is an input signal; $A_k$, $\omega_k$, and $\theta_k$ are the amplitude, frequency and phase, respectively, of the $k^{th}$ sinusoid; and $r(t)$ is the residual component of the signal at time *t*.

In developing the virtual bone surgery system, Niu and Leu (2007), conducted experiments to record sound clips from the drilling of different bone materials, and the power spectra of those sounds were obtained by Fast Fourier Transformation (FFT). It was found that the power spectra of sounds obtained from the drill's free running, cortical bone drilling and cancellous bone drilling were all similar, as shown in Figure 16. Compared to free running, bone drilling influences primarily the amplitudes of the sound spectrum at peak frequencies, although the frequencies of some of the spectral peaks may shift slightly. The level of sound generated from the drilling of cortical bone material is higher than that generated from the drilling of cancellous bone material, indicating that the denser the bone material, the higher the sound amplitude.

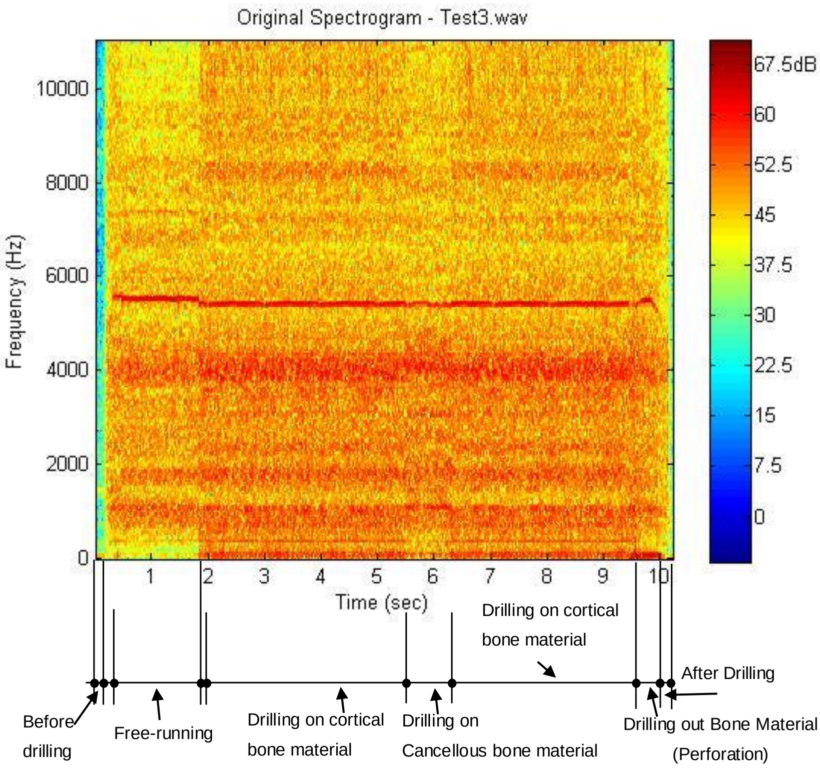



**Fig. 16 Different stages of drilling in the bone material (Niu, 2008)**

Niu (2008) performed spectral modeling on various bone drilling sounds to obtain the sinusoidal and residual parts for each of these sounds. It is shown that the resulted residual parts shared a high level of similarity. Therefore, in the synthesis of bone drilling sounds, the residual part was kept the same as that obtained from the free running sound, and only the sinusoidal components were varied. Magnitude changes and frequency shifts, if any, were then applied to the sinusoidal components for generating the synthesized sounds for cortical bone drilling and cancellous bone drilling. The input peak frequencies, magnitudes and phases were transformed into time-domain sinusoids and then added together frame by frame, called the additive synthesis process. The synthesis of the residual part of the sound took the residue's enveloped spectrum, and the Inverse Fast Fourier Transform (IFFT) with a window function was applied to this spectrum to generate a stochastic signal in the time domain. Finally, the sinusoidal and residual parts were added together frame by frame to create the synthesized sound.

### 1.7.2 SOUND RENDERING

Sound rendering, first introduced by Takala and Hahn [1992], is a technique of generating a synchronized soundtrack for animations in a virtual environment. The synthesized sound in the time domain can be used for sound rendering in a virtual bone surgery system. The result of sound rendering generates the sound output to the suitable hardware (sound card, loudspeaker, etc.) for the user to hear the sound. For auditory rendering of the synthesized sound, the virtual bone material removal system can communicate with a sound card on a PC and create sound buffers using Microsoft MS-DirectSound API. A set of sound signals including the sinusoidal and residual parts could be generated and placed in the secondary buffers, with the DirectSound adding these signals and writing the result into the primary buffer to render the sound (Niu, 2008).

## 1.8 CONCLUSION

Developing a bone surgery simulation system is a major undertaking and poses many technical challenges. The overarching objective of such a development is to build a high-fidelity simulation system which incorporates the latest technologies in virtual reality including computer graphics, haptics, and auditory rendering. This book chapter reviews the current bone surgery simulation systems, and the methods and techniques used to develop such systems.

The described virtual bone surgery system development consists of the following tasks: image processing, geometric modeling, physical modeling, graphic rendering, haptic rendering, and auditory rendering. A virtual bone surgery system usually takes preprocessed CT or MRI image data to construct a geometric model of the bone and soft tissue using volume or surface modeling methods, and update the geometric model continuously during the virtual surgery. Special data structures such as octree or bounding volume plus quadtree are used to handle the large set of medical data. To perform graphic displays in real-time, surface rendering with a marching cube algorithm is used in most virtual bone surgery systems. For force feedback, physics-based models are used to represent the interface forces between the surgical tools and the bone/soft tissue in deformation and material removal. Auditory rendering can play an important role in the generation of an immersive virtual environment, and the sound can be modeled by physical modeling or spectral modeling. Overall, graphic rendering, haptic rendering, and auditory rendering are generated in real-time using multithreading computations to provide realistic graphic, haptic, and auditory feedback during the bone surgery simulation.

Research and development work on virtual bone surgery is far from mature. An ideal virtual bone surgery system should be able to provide high-fidelity dynamic graphic displays with realistic force and sound feedback during the simulated surgery process. In the future, with new emerging computer hardware, new algorithms and technologies, it would be possible to increase the level of realism by adding more virtual reality aspects to the bone surgery simulation system. For example, more realistic force, sound and visual effects such as bleeding, debris formation, and fluid flow in the bone surgery, could be included to make a virtual bone surgery system more immersive, intuitive, and interactive.

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