Chapter e21

Computer-Assisted Medical Education

21.1 INTRODUCTION

This chapter is dedicated to educational applications of medical visualization techniques. Interactive 3D visualizations have great potential for anatomy education as well as for surgery education, with users ranging from high school students and physiotherapists to medical doctors who want to rehearse therapeutical interventions. Computer-assisted training systems enhance surgical manuals, surgical courses, and cadaver studies by providing up-to-date multimedia content. In particular case-based systems with self-assessment tools support problem-oriented learning and thus potentially improve problem-solving capabilities.

Recent advances include web-based systems that enable personalized access with an individual profile and a list of favorite entries, as well as possibilities to upload content and discuss with colleagues. Among the potential users, case-based e-learning and interactive use of 3D models have also gained reasonable acceptance. In a recent survey, the majority of 176 German medical students answered that they like using such systems for educational purposes and for preparing exams [Birr *et al.*, 2013]. In the same survey, it turned out that most multimedia systems based on canned drawings are criticized because of their low level of interactivity. However, the actual experience of medical students with interactive 3D visualizations is low. Thus, carefully designed and easy-to-use systems are required to stimulate the proliferation of educational systems based on interactive 3D visualizations.

The Role of Visualization Techniques While advanced visualization techniques currently play only a minor role, they have the potential to enhance the display of complex interventions. Among the few systems having adopted advanced visualization techniques at an early stage is the VoxelMan, an anatomy education system that even gave rise to the development of new visualization techniques, such as high-quality rendering at subvoxel accuracy and advanced vessel visualization.

Surgical Simulators The most complex systems targeting on medical education are surgical simulators that aim at providing a realistic virtual environment for practicing complex surgical interventions.

Many challenging tasks have to be solved to provide a convincing environment: Force feedback when tissue is touched or penetrated, collision detection, soft tissue deformation, cutting, and the simulation of various complications. We discuss these problems and focus on the interactive visualization techniques used in these settings. In addition, we discuss the design of such systems, the selection and structure of the underlying content and aspects of validation. In particular, the assessment of skills acquired with a training system, and the relevance of the acquired skills for clinical practice, have gained much attention in recent years.

Increasingly, simulators are also employed for catheter-based interventions, where assistant doctors have to learn the selection of catheters and their deployment for complex vascular interventions. These interventions have many advantages for the patient, including reduced trauma and postoperative pain, but they exhibit inherent problems and pitfalls for the surgeon due to the small size of the incision through which all actions have to be performed. These problems include the lack of dexterity due to the loss of two degrees of freedom (instruments can only be moved forward or backward), the lack of fine-manipulation, and the degradation of force feedback in the interaction with human tissue which is

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essential for the palpation of the patient [Tavakoli *et al.*, 2006]. We describe some of the general problems, such as modeling elastic tissue properties, collision detection, simulating soft tissue deformation, and adequate force feedback.

We primarily discuss applications in anatomy, interventional radiology, and different surgical disciplines. This is motivated by the benefit of interactive rendering of volume data and derived 3D models in these areas. Computer support may enhance education in selected medical disciplines. However, traditional forms of learning, such as lectures, and dissections of cadavers or physical models, as well as giving assistance during surgical interventions, shall not be replaced by any software solution.

Training with Physical Models Another recent trend is the use of physical models derived from medical image data and produced with rapid prototyping technology. Segmentation and surface extraction are two essential steps related to the topic of this book. Due to progress in manufacturing technology, physical models are becoming much more affordable and at the same increasingly flexible with respect to the materials used. The great potential of physical models is that they may represent a variety of pathologies and enable the use of real surgical instruments. The emerging use of physical models is primarily motivated by the shortage of cadavers available for surgical training.

Organization As a basis for the discussion of case studies, we introduce general concepts of computer-based training (§ 21.2) and metaphors for educational systems. Case studies in anatomy education (§ 21.3) and surgery education (§ 21.4) follow. The second part of the chapter is dedicated to systems that *train* procedures, instead of only presenting interactive multimedia content. This part starts with a discussion of the underlying techniques (§ 21.5), including haptics, collision detection, and soft tissue simulation. Case studies (simulation systems) in interventional radiology (§ 21.6) and surgery (§ 21.7) follow. We introduce simulation technology that employs rapid prototyping to enable training with physical models (§ 21.8). Finally, we discuss *skills assessment*, that is, concepts and systems that assess what was learned using a computer-assisted training system (§ 21.9).

21.2 e-LEARNING IN MEDICINE

e-learning systems in medicine have been used for almost 50 years [Owen *et al.*, 1965]. Due to the widespread availability of suitable computers and enhanced use of the multimedia presentation capabilities, the interest and popularity of e-learning has grown in recent years. Many experiments showed that the combination of presenting knowledge simultaneously with audio and video materials increases the retention of knowledge considerably [Mehrabi *et al.*, 2000].

Although the initial costs of e-learning development are considerable, these systems can be updated more flexibly compared to traditional media. Also, the mode of presentation used in state-of-the-art e-learning systems is considered to be superior. It turns out that the large majority considered e-learning as useful, as a substantial help in self-study and exam preparation. In recent years, this also lead to broad acceptance of such education systems.

Constructivism and Situated Learning Chittaro and Ranon [2007] further elaborate on the pedagogical motivation, in particular of interactive 3D visualization. *Constructivism* is a fundamental pedagogical theory according to which learning primarily occurs if trainees are "engaged in meaningful tasks." According to this theory, when we interact with an environment (a real or simulated environment), this enables direct, even unconscious experience and thus an increased *depth of experience* compared to, e.g., learning from listening to a teacher or reading a textbook. In essence, we *construct* the knowledge as learners ourselves. Among the medical education system explicitly mentioning constructivism as guiding theory is the anatomy teaching system ZYGOTE BODY [Kelc, 2012].

Another relevant concept of pedagogic theory is *situated learning*—a concept where learning experiences are provided in a context that is very similar to situations where this knowledge should be applied. Thus, surgery simulation or surgery training with physical models and real surgical instruments represents a setting where situated learning is possible. For education in medicine, an advantage of e-learning is that clinical pictures are represented graphically.

Learning Objectives General concepts and rules of thumb for e-learning systems should be considered in the design and evaluation of educational systems for anatomy and surgery. e-learning systems should be based on a clear understanding of *learning objectives* and the *target user group*. The processes to acquire this understanding are known as *task analysis* and *audience analysis* [Lee and Owens, 2000] (recall Chap. 5). The design of e-learning systems is a special aspect of interactive system design. Therefore, textbooks on this topic, such as [Shneiderman and Plaisant, 2009] are relevant here. In particular, the scenario-based approach to user interface design, advocated by Rosson and Carroll [2003], is highly recommended and has been proven successful in e-learning projects, such as the SPINESURGERYTRAINER [Kellermann *et al.*, 2011] and the LIVERSURGERYTRAINER [Mönch *et al.*, 2013]. The core idea of this approach is that developers and users agree on essential scenarios, sequences of user input and system output described informally in natural language. These scenarios should guide the analysis stage, the prototyping activities, user evaluations as well as the documentation of interactive systems (recall § 5.2.3.2).

e-learning systems should provide a *self-steered* and *directed* method of learning. With e-learning systems, users can "pick an individual learning pace" [Mehrabi *et al.*, 2000]. A path to the learning environment that can be followed, left and re-entered freely, is necessary. It is essential that users can explore the material, for example by interrogating graphical representations, by answering multiple-choice questions or by solving tasks which involve a manipulation of graphical objects.

Examples for learning objectives in anatomy are the following. Students should be able

- to locate certain structures,
- to know the functional relation between certain structures, and
- to recognize typical variations of certain structures.

Learning objectives should be explicitly specified, and they should guide the design and development of e-learning systems. The analysis and understanding of learning objectives may serve as a basis to guide the user and provide an appropriate learning experience.

Success Criteria In summary, to enable successful learning, e-learning systems should:

- provide realistic and *appealing examples*,
- support *active participation* where users not only observe prepared sequences of images, textual description, and animation, but have to make decisions and to solve tasks,
- provide *adequate feedback*, in particular when the user solved a task,
- provide *self-assessment tools*, such as quizzes or multiple-choice questions,
- allow the user a *flexible exploration* of tasks and material with navigation aids telling the user what has been done and what could be done next.

Finally, the success of e-learning systems also depends on the motivation of learners. If the use of an e-learning system is perceived as diligent work only, few users will fully exploit its capabilities. The study of techniques from the area of computer games may help to get inspirations for combining learning with an entertainment experience.

e-learning in Anatomy and Surgery In medicine cognitive and motor skills are important. *Cognitive skills* comprise factual knowledge, e.g., names of anatomical structures, and knowledge of procedures, e.g., the selection of a basic treatment, the steps to be performed, complications, follow-up and postoperative management. *Motor skills* comprise psychomotor skills to actually perform a procedure, e.g., to apply the right amount of pressure to insert a catheter in a vascular tree or to perform suturing and knot tying in laparoscopic surgery. Cognitive skills may be verified with a quiz or multiple-choice questionnaires [Oropesa *et al.*, 2010]. The training of motor skills requires training systems which enable to practice the actual procedure. The assessment of motor skills is largely performed by observations from experts and by some automatic measures, related to dexterity. The assessment of motor skills is far less standardized compared to cognitive skills assessment [Oropesa *et al.*, 2010].

e-learning systems for anatomy and surgery education focus on the acquisition of cognitive skills. They require appropriate image data and segmentation results. Based on these data, high-quality renderings can be generated and interactively explored as an essential component of such e-learning systems. Thus, in addition to the above-mentioned general requirements for e-learning systems in medicine, there are some further requirements for systems related to image data, e.g., in radiology and surgery. These systems should:

- provide 2D visualizations with overlays representing segmentation results,
- provide high-quality 3D models and related visualizations to explore spatial relations, e.g., margins and vascular supply areas,
- provide *integrated* 2D and 3D visualization with synchronization, e.g., when objects are selected,
- provide easy-to-use interaction facilities, such as incremental rotation.

While clinical applications require fast segmentation and visualization, educational systems require primarily high-quality results. By the way, the accuracy of visualizations is less important. Smooth surfaces without distracting features are preferred.

21.2.1 DATASETS FOR MEDICAL EDUCATION

Datasets play a key role in medical education. High resolution datasets with a good signal-to-ratio and only few artifacts enable the detailed exploration of anatomical structures. The acquisition of such datasets requires considerable experience, appropriate infrastructure and thus is expensive. Fortunately, the best datasets are publicly available and triggered a boost of educational systems.

Visible Human The most widely used data sources for anatomy education are the Visible Human datasets. These 3D datasets originate from two bodies that were given to science, frozen, and digitized into horizontally spaced slices. A total number of 1871 cryosection slices were generated for the Visible Man (1 mm slice distance) and even more for the Visible Woman (0.33 mm slice distance). Besides photographic cryosectional images, fresh and frozen CT data, as well as MR images, were acquired. The project was carried out at the University of Colorado (Head: Dr. Victor Spitzer) under contract of the National Library of Medicine, Bethesda, Maryland [Spitzer *et al.*, 1996, Spitzer and Ackerman, 2008].

The Visible Human datasets have a high quality that was unprecedented at that time (1994). For example, CT data were acquired with high radiation—resulting in an excellent signal- to-noise-ratio—and without breathing and other motion artifacts. However, the quality of the data is not perfect: The frozen body was cut in four blocks prior to image acquisition leaving some noticeable gaps in the data.

FIGURE e21.1 *Photographic data from the Visible Human Male dataset.* ***Left:*** *a slice view.* ***Right:*** *a volume rendering with clipping enabled (From: [Tiede et al., 1996]).*

The Visible Human datasets are employed for a variety of educational systems, e.g., the VoxelMan for anatomy education [Höhne et al., 2003] and many training systems for interventional radiology and surgery. Figure e21.1 shows examples of the Visible Human cryosections.

Visible Korean and Chinese Visible Human Datasets from people of other regions in the world were also needed for medical education. In the "Visible Korean Human" project, a dataset of a 65-year-old patient was provided [Park et al., 2006]. The Chinese Visible Human avoided some problems of the original Visible Human project [Zhang et al., 2006a]. In particular, the image acquisition was performed with a very large milling machine that did not require to cut the body. Thus, the section loss, which occurred in the Visible Human project as a result from cutting the body, could be avoided. Also smaller details were better preserved and did not fall from the milling machine. In contrast to the Visible Korean Human, the Chinese dataset contains normal female and male adults. The Chinese Visible Human also exhibits a superior spatial resolution (in-plane resolution 170 μm). The raw data (photographs, CT and MRI data) is not sufficient for medical education systems. The precise segmentation of the target structures is another essential prerequisite. In a long-term effort, 869 segmented structures of the male dataset and 860 of the female dataset were provided [Wu et al., 2012b].

Further Anatomical Data and Outlook The University of Colorado, Center for Human Simulation, where the Visible Human datasets were acquired, continued its efforts to acquire anatomical data at a very high quality. Spitzer and Ackerman [2008] provide a survey on datasets acquired between 2003 and 2008. The dataset with the highest quality represents the foot and ankle region with 5000 visible light photographs acquired in 2007, see Figure e21.2. This increased resolution resembles high magnification images from arthroscopy and indeed is used for an arthroscopy simulator showing ligaments and tendons in an excellent quality. Other datasets represent the prostate and pelvis region, the wrist and hand as well as the thorax and heart region.

Still, the number and quality of such datasets does not fulfill all requirements for medical education. A larger diversity of datasets representing various pathologies is desirable. For some applications, data are needed in a special configuration, e.g., some diagnostic and treatment procedures require flexing the neck

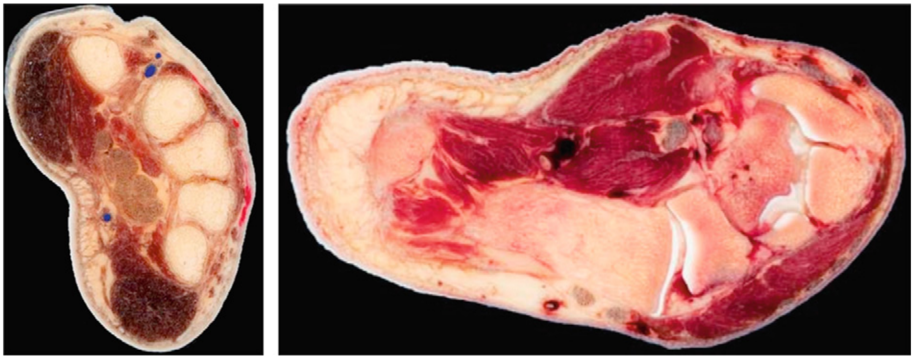

FIGURE e21.2 *Two cross-sectional views of datasets with improved resolution compared to the Visible Human datasets.* ***Left:*** *Cross section of a wrist dataset.* ***Right:*** *A slice of a foot and ankle dataset of a young female. Data were cut every 0.05 mm (From: [Spitzer and Ackerman, 2008]).*

as much as possible. Spitzer and Ackerman [2008] report on ongoing work to simulate the movement of ligaments and spinal nerves depending on the movement of the vertebrae.

Clinical Data An alternative source of data are high-quality clinical data which represent the variety of anatomical structures and pathologies. As an example, the first versions of the VoxelMan were based on a cerebral MRI dataset [Höhne *et al.*, 1992]. For anatomy education, some care is necessary to use data from a healthy person with normal anatomical relations. If anatomical differences should be compared, the selection of cases should be representative with respect to typical variants.

The segmentation of these datasets can be accomplished with general segmentation techniques (recall § 4.3). A special aspect is the segmentation of photographic datasets of the different Visible Human projects. These datasets represent colored voxels (24 Bit per voxel, representing a red, green, and blue component). The segmentation of colored data in RGB space is described by Schiemann *et al.* [1997].

For anatomy education, in principle all anatomical structures which can be derived from the image data are relevant. The VoxelMan, for example, is based on the segmentation of 650 objects (clinical applications often require the segmentation of fewer than 10 objects). The identification and delineation of functional areas in the brain requires considerable expert knowledge, since these areas are not represented as recognizable objects in the image data.

Geometric Modeling Segmented medical image data are the basis for 3D visualizations, but a dedicated effort is required to obtain high-quality 3D models. A simple surface extraction leads to aliasing effects. Therefore, smoothing, e.g., by subdividing and simplifying polygonal meshes is desirable [Brenton *et al.*, 2007]. High-end systems even add realistic textures, e.g., to convey the structure of muscles. Specialized modeling tools are employed for these purposes. The most comprehensive tools were developed for the film-making industry, where realistic appearance and behavior of virtual characters is essential. Maya is among such tools and used for example by Brenton *et al.* [2007] to create high-quality models (see Fig. e21.3).

Applications The Visible Human datasets have been employed for numerous medical education systems. Prominent examples are the VoxelMan [Pommert *et al.*, 2001], the VoxelMan Temporal Bone Simulator [Zirkle *et al.*, 2007] and an arthroscopy simulator to train endoscopic examinations of the knee

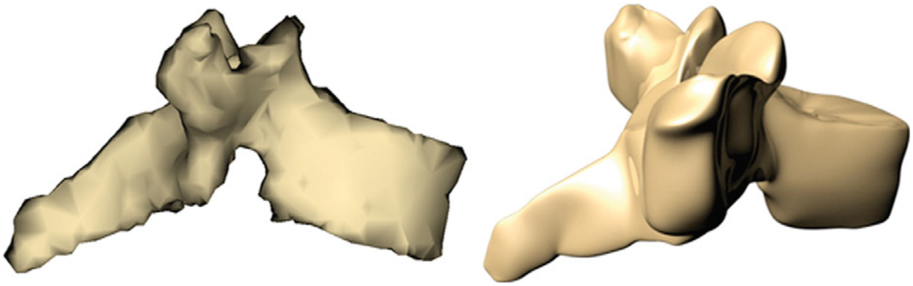

FIGURE e21.3 **Left:** *Surface extraction from the Visible Human dataset leads to a noisy surface of vertebrae.* **Right:** *After subdivision with Maya a smooth appearance results that is more appropriate for anatomy education* (From: [Brenton et al., 2007]).

[Heng et al., 2004a]. The training system for lumbar punctures, developed at the University of Lübeck [Färber et al., 2009, Fortmeier et al., 2013b], employs both the Visible Human and the Visible Korean dataset. Also a variety of other needle-based interventions were trained by means of these datasets. Even a whole journal, the Visible Human Journal of Endoscopy,[1] was founded, presenting papers where findings are correlated with Visible Human images, particularly with endoscopic views.

Spitzer and Ackerman [2008] give an overview of 15 years of using the Visible Human datasets, emphasizing how strongly 3D stereo visualizations of the data have been used for anatomy education at many sites in the US. They summarize the impact of the Visible Human datasets as follows: "The assignment of physical properties, the development of algorithms for interaction of surgical tools with this virtual anatomy and the availability of high-fidelity haptic interfaces provide the basis for fully immersive surgical training and certification." In the course of this chapter, we shall get to know many of these applications.

21.2.2 KNOWLEDGE REPRESENTATION

Although interactive visualizations are the primary components of medical education systems, they are not sufficient to effectively support learning processes. The mental integration of visual elements and related symbolic knowledge is an essential learning goal. Symbolic knowledge relates to concepts, names, and functions of anatomical objects and to various relations between them, for example, which area is supplied by a certain vascular structure. Knowledge representation schemes employ segmentation information and allow for the addition of various relations between individual objects. Before we actually discuss knowledge representations, it should be noted that anatomy is studied according to its different subdivisions. Important subdivisions of anatomy are (cf. http://www.webanatomy.com/, accessed: April 30, 2013):

- *clinical anatomy*: the study of anatomy that is most relevant to the practice of medicine.
- *comparative anatomy*: the study of the anatomies of different organisms, drawing contrasts and similarities between the structure and function of the anatomies.
- *cross-sectional anatomy*: anatomy viewed in the transverse plane of the body.
- *radiographic anatomy*: the study of anatomy as observed with imaging techniques such as conventional X-ray, MRI, CT, and ultrasonography. Images which relate to cross-sectional and radiographic anatomy are shown in Figure e21.4.
- *regional anatomy*: the study of anatomy by regional parts of the body, e.g., thorax, heart, and abdomen. In regional anatomy, all biological systems, e.g., skeletal, and circulatory, are studied with an emphasis on the interrelation of the systems and their regional function.

1 http://www.vhjoe.org/.

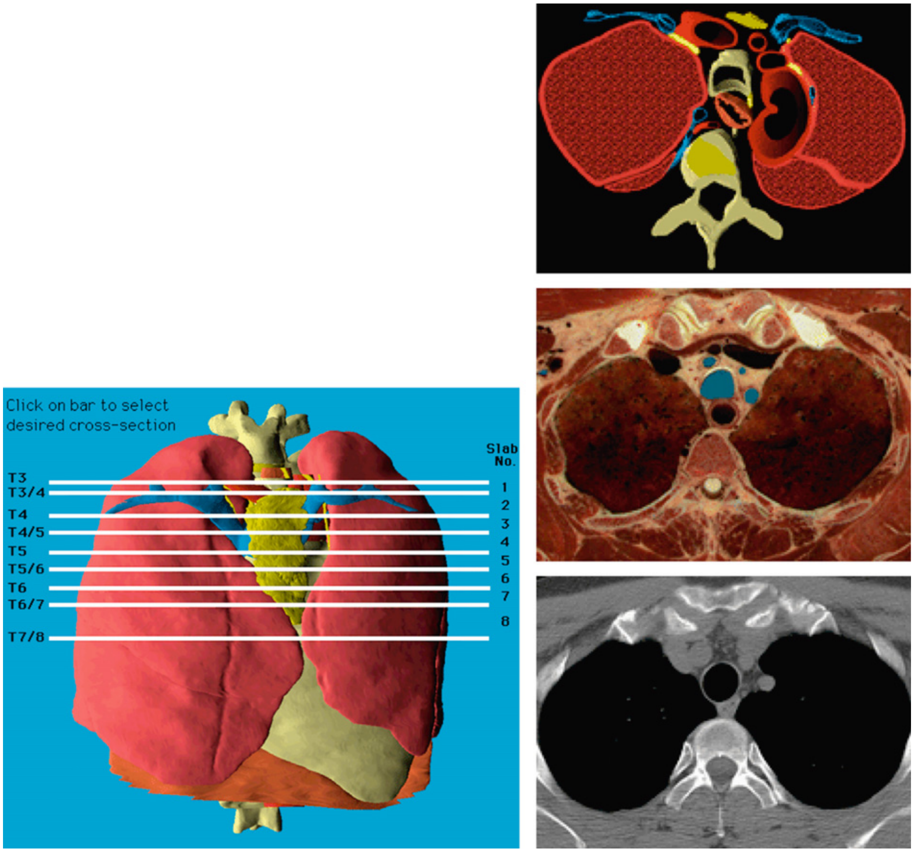

FIGURE e21.4 *A 3D overview (left) is used to show different levels for which cross-sectional and radiographic images are provided. The images on the right relate to the T1 level in the left image (Screenshot of the Digital Anatomist).*

- *systemic anatomy*: the study of anatomy by biological systems, e.g., skeletal, muscular, and circulatory system. In systemic anatomy, a single biological system is studied concurrently across all body regions.
- *macroscopic anatomy*: the study of anatomy with the unaided eye, essentially visual observation. Typically, macroscopic anatomy is explored using dissected cadavers.
- *microscopic anatomy*: the study of anatomy with the aid of the light microscope and with electron microscopes that provide subcellular observations. Microscopic anatomy is based on very high resolution images, and provides insight at a level which is not possible with tomographic image data or with dissecting cadavers.

These different aspects of anatomy form different "views" on the anatomy. For example, the kidney is part of the abdominal viscera in the *regional anatomy* and part of urogenital system in the *systemic anatomy* [Pommert *et al.*, 2001].

Ideally, e-learning systems for anatomy comprise and integrate all aspects, for example by smoothly blending in data in different resolutions. There is some progress toward this vision in recent years, e.g., in some surgical simulators that blend microCT and CT data, but the technical problems with respect to data size and handling are still challenging. Clinical anatomy and radiographic anatomy can be explored with medical volume data and derived information. As an example of combining different aspects of anatomy, the DIGITAL ANATOMIST [Brinkley *et al.*, 1999] provides 3D overviews where the positions of certain slabs are marked (Fig. e21.4). For each slab, the related information is shown as CT slice, as photographic data and as clipped 3D visualization. Users may zoom, rotate, and label anatomical structures. Also 15 neurological pathways (recall Chap. 15) and 18 histologic dissections are illustrated.

e-learning for the study of *comparative anatomy* requires a variety of different datasets (along with segmentation results) that represent at least the typical anatomical variants. As an example, hepatic vasculature may exhibit variants, such as an (additional) accessory hepatic vein, a trifurcation of the portal vein main branch or inferior veins [Birr *et al.*, 2013]. Most e-learning systems do not support this important aspect of anatomy.

Many anatomy education systems focus on *regional anatomy* and represent the relation between labels and segmentation results. Some systems provide textual labels and related textual explanations with facilities to explore them along with the graphical representation [Preim *et al.*, 1997]. A sophisticated representation of symbolic anatomical knowledge however goes far beyond this and effectively builds an ontology composed of different views, e.g., different kinds of relations between anatomical objects. The first advanced (digital) knowledge representation for anatomy has been developed by Schubert *et al.* [1993]. Among others, they represent:

- *part-of relations* (one object belongs to a larger object, for example a functional brain area),
- *is-a relations* which group anatomical objects to categories,
- *supplied by relations*, which characterize the blood supply.

This knowledge is integrated in a *semantic net*—a flexible knowledge representation (see Fig. e21.5). The relation between variably labeled volumes and the symbolic knowledge is referred to as *intelligent voxel*. This relation provides the basis to interactively interrogate parts of graphical representations. Similar concepts for knowledge representation have been used later for the DIGITAL ANATOMIST [Brinkley *et al.*, 1999] and the ANATOMYBROWSER [Kikinis *et al.*, 1996a] (see § 21.3). Smit *et al.* [2012] have recently extended these concepts to support completely free-form relations between arbitrarily represented, i.e., not necessarily voxel-based, anatomical structures.

While such knowledge representations are primarily discussed for anatomy, they are also relevant for operative medicine. Knowledge representations supporting operative disciplines may incorporate instruments, typical resection areas, and puncture points in their relation to anatomical structures.

Primal Pictures PRIMAL PICTURES contains a comprehensive set of anatomy-related and physiology-related educational systems. Primal Pictures is based on geometric models with an excellent quality that can only be achieved with substantial anatomical illustration know-how, e.g., with respect to the use of colors. The interactive handling of these 3D models was performed by means of VRML. The first generation of web-based 3D visualization systems was based on specialized formats and plugins, most notably VRML (virtual reality markup language). VRML was also used for medical education, e.g., in Primal Pictures. According to the different subdivisions of anatomy that we have described in § 21.2.2, Primal Pictures is focused on regional, systemic, and cross-sectional anatomy. As an example for *systemic anatomy*, modules are provided that convey the dynamics of moving muscles, ligaments and their influence on skeletal structures. Dedicate modules are available, e.g., for illustrating the knee and its dynamics, the hand and the hip. Interactive 3D visualizations are provided along with textual labels and explanations.

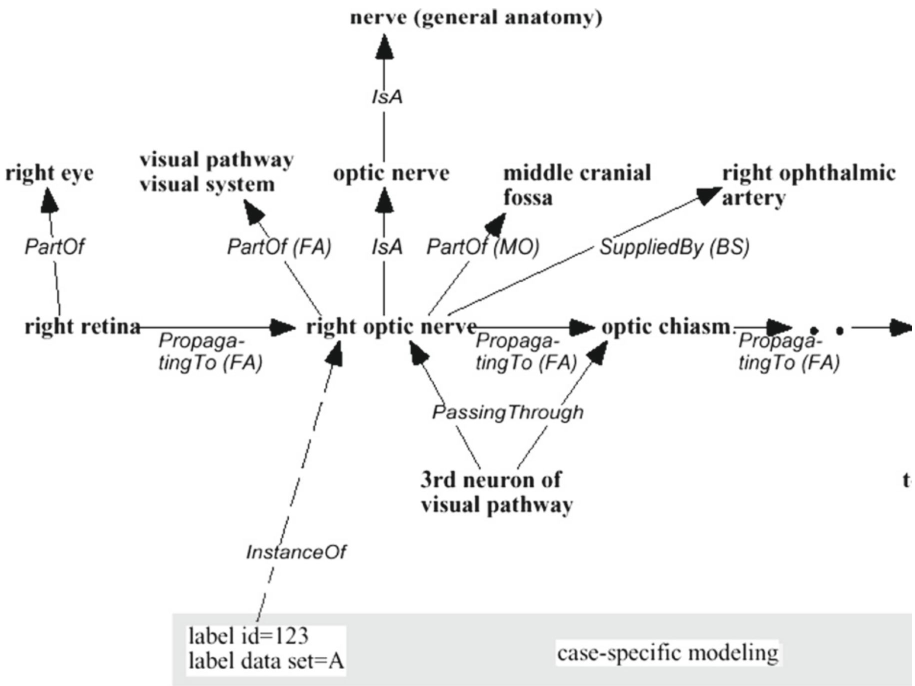

FIGURE e21.5 *A semantic net describes anatomical knowledge and serves as a basis for interactive interrogation (Inspired by [Schubert et al., 1993]).*

21.2.3 WEB-BASED MEDICAL EDUCATION SYSTEMS

The full potential of computer-assisted education systems may only be exploited with web-based systems. The access to such systems is not limited to any location or to a specific device. In particular, advanced anatomy and surgery training systems, such as surgical simulators, were developed with proprietary tools and relied on very specific hardware limiting access to very small groups of people. We discuss web technology and open standards here, since systems based on such technology tend to provide "easier reuse, easier integration with existing content and lower price" [Chittaro and Ranon, 2007].

Web-based learning is often classified into (cf. [Chittaro and Ranon, 2007]):

- tutorials,
- online discussion groups, and
- virtual patients.

Tutorials relate to content provided by an expert, usually including different media and links, e.g., to further information, such as publications. Discussion groups emphasize joint activities facilitated by web-based systems, including discussions between teachers and trainees. In the medical education terminology, *virtual patient* is a term that includes the visualization and interaction of patient data including all kinds of simulations and animations, e.g., to show the effect of treatment.

21.2.3.1 Potential and Limitations

The potential of web-based learning in general and in medicine in particular has often been discussed: Rich content may be provided and even adapted to the individual learner and thus provide an engaging learning experience. There are some further advantages, e.g., learning experiences may be documented automatically.

However, as Cook [2007] discusses based on substantial experiences with many web-based learning systems, this potential is very difficult to exploit fully; there are clear limitations and disadvantages. Online discussion cannot fully replace the social interaction that occurs in face-to-face meetings, for example, and subtle technical problems are difficult to avoid and may disturb significantly.

In particular, the promise of an individualized and *adaptive learning experience* that compensates for differences in baseline knowledge, learning and cognitive styles is very difficult to realize in practice, despite a large body of research on such adaptation processes (see e.g., [Brusilovsky, 2003]). Cook [2007] argues that a teacher is usually better able to adapt the presentation in small groups to such differences.

21.2.3.2 Essential Design Aspects

In addition to all general aspects on good user interface design discussed in Chapter 5, there are a number of specific aspects in designing web-based learning. They are described concisely in a step-by-step approach by Cook and Dupras [2004]. We want to highlight one aspect because of its great importance for designing learning systems: *Active learning* should be encouraged. This includes the provision of mechanisms to *apply knowledge*, and the support of *problem-based learning* instead of abstract principles and self-assessment. They present a detailed explanation, citing many successful examples to realize this principle, and conclude with "The degree of success in this area will in large part determine the effectiveness of the educational website." Later, we discuss at various stages how this principle is realized in practical systems.

21.2.3.3 Web Technology

VRML The potential of web technology for providing unlimited access to interactive 3D visualizations led to the definition of VRML in 1994. VRML, the virtual reality markup language, later became an official ISO standard in 1997. Based on the OPEN INVENTOR specification, VRML employs a scene graph description of a 3D model, that is a direct acyclic graph that represents the geometry, material properties, e.g., colors and transparency, textures, 2D and 3D text, transformations, light sources, and the virtual camera. A polygonal surface, for example extracted with the Marching Cubes algorithm, is represented as an "IndexedFaceSet" node. This memory-efficient scheme comprises the coordinates of vertices and the association of these vertices to faces avoiding any redundancy. All major visualization toolkits enable VRML export of the results.

In addition to the geometry, also the behavior is represented in nodes of the scene graph, e.g.,

- with sensors that observe certain properties and may trigger a reaction,
- with manipulators that may control clipping planes or other widgets, and
- with nodes that enable collision detection, e.g., to detect whether a surgical instrument touches an anatomical structure.

An essential aspect for creating feature-rich medical education applications is the combination of Java and VRML.

VRML was also widely used for developing medical education systems. John [2007] provides an overview categorizing systems in general tools for medical education, educational tools for diagnosis and procedure training as well as collaboration support. As an example, Brodlie *et al.* [2000] presented VRML-based prototypes for vascular surgery and neurosurgery. However, the low bandwidth in the 1990s and the requirement to install a VRML browser at the client side hampered widespread use. In addition, 3D interaction and navigation was often very difficult. Thus, trainees easily became lost in the 3D environments or were confronted with an overwhelming number of options.

X3D and WebGL X3D (extensible 3D), like VRML, is an open ISO standard defined by the W3 consortium and thus it is independent of any specific platform. It is largely backwards-compatible with VRML. Thus, VRML files need only minor adaptation to be used as X3D files [Chittaro and Ranon, 2007]. The development of X3D was triggered by progress in graphics hardware, in particular improved programming capabilities and multitexturing. Thus, it provides a number of new nodes and capabilities. In addition, X3D files may also be encoded in XML and thus easily mixed with other content that is available in XML. Often, it is advantageous that also a memory-efficient binary encoding of X3D data is provided.

HTML5 references X3D for declarative 3D content but does not define the actual integration. X3DOM[2] was developed to integrate X3D in web applications directly [Behr *et al.*, 2009]. The mapping of live DOM elements to a X3D scene model is very similar to the integration of interactive 2D vector graphics via SVG [Behr *et al.*, 2009]. Such a direct integration not only provides advantages for the users, namely that no plugin needs to be installed. Also developers benefit because synchronization problems between DOM content and plugin-based manipulations are avoided and of course also because developers do not need to focus on the peculiarities of just one plugin. Behr *et al.* [2009] described the X3DOM architecture in detail and compares it with various other approaches of integrating interactive 3D graphics with web browsers. Implementation strategies for X3DOM are explained in [Behr *et al.*, 2010]. More recently, Behr *et al.* [2011] introduced a multitude of advanced mechanisms for supporting dynamics (animations) and 3D interactions with appropriate events and update mechanisms. Finally, Behr *et al.* [2012] introduced a separation of the large and unstructured geometry data from the structured (and much smaller) scene information to improve handling and performance.

The "Medical Working Group" has defined MedX3D that adds advanced volume rendering and transfer function specification to X3D. This extension is essential, e.g., for surgical simulators, where tasks, such as drilling, require voxel representations [John *et al.*, 2008, Jung *et al.*, 2008]. The "long-term goal of the working group is to enable the creation of interoperable medical training and simulation systems using open standards" [John, 2007]. Currently the working group is engaged with the DICOM Working Groups and are proposing X3D as the DICOM 3D Graphics standard.[3]

In 2012, after demonstrating that the extensions fulfill the needs of key applications in medical diagnosis, treatment and education, this extension was officially integrated in the ISO standard X3D as "Volume Rendering Component." This extension is comprehensive and supports a large variety of rendering and illumination styles, such as cartoon rendering. Like the core of X3D, the volume rendering is specified as a scene graph, containing *scene graph nodes* that define the geometry and appearance of individual components, such as subvolumes or surgical instruments.

With the introduction of WebGL as part of HTML 5, advanced 3D visualization in the web browser, without the need to install a plugin, has become possible. WebGL is a low-level graphics API based on OpenGL ES 2.0 and enables hardware-accelerated rendering of 3D graphics. It supports mobile rendering and efficient shader programming. Frameworks such as X3DOM can utilize WebGL to perform 3D rendering.

2 http://www.x3dom.org/.
3 Nigel John, personal communication.

21.2.4 WEB 2.0 IN SURGICAL EDUCATION

Web 2.0 represents an enhanced use of the web. Instead of a few authors providing content and many receivers using that content in the intended way, users may annotate, comment, and link the content as well as provide content themselves. Prominent examples are social networks, such as FACEBOOK and LINKEDIN, but also video platforms, such as YOUTUBE. Professional networks, such as LINKEDIN, may serve as orientation with respect to attributing capabilities and experiences to users.

For medical education these concepts are attractive as well. However, medical doctors as target user group and patient data as content represent a very special situation that demands dedicated solutions. A web-based educational environment enables the distribution of carefully prepared content, such as segmented medical data and related 3D visualizations. Informed consent by patients and strict anonymization are, of course, mandatory. User-generated content is more difficult to manage—the system evolves in a way that is hard to predict. At least certain categories should be prepared. In addition keywords are necessary to enable efficient search.

At the time of writing, a German research project aiming at exploiting Web 2.0 technology for surgery education is being concluded, hopefully followed by a stage where the platform is extensively used. The design of the platform, called SURGERYNET, is guided by general functionalities for social platforms [Richter and Koch, 2008]. Thus, a social platform should provide rich features for

- exchanging information,
- identity management (decisions related to the visibility of information),
- contact management, including contacts to leading experts, and
- context awareness, making individual users aware of their peers and the common goals and activities.

Franken and Jeners [2012] explain how this basic functionality is realized for web-based surgery education. SURGERYNET also provides a conference calendar, hints to live operations that may be observed, but also contributions from industrial suppliers, e.g., related to the use of new surgical instruments.[4] Users may create comprehensive profiles, link to other users, create lists with contributions relevant to them and create bookmarks within the text. They may create exchange folders, invite colleagues to view and edit material and thus cooperate in a flexible and powerful manner. Figure e21.6 presents an example.

In contrast to most other platforms, SURGERYNET has no strong editorial board that acts as filter for new content but instead encourages a more spontaneous upload of content by users. Probably high-quality contributions are viewed more often, better assessed and then displayed more prominently leading to an *implicit quality control* that is more consistent with the general Web 2.0 philosophy. With this philosophy, the content is not that strictly categorized (although categories and keyword lists for tagging are suggested), and a larger variety of content may be provided.

An annotation tool is integrated with SURGERYNET in order to define and emphasize anatomical structures as well as to label them (see Fig. e21.7). This web-based annotation tool is intended to author a contribution, e.g., an interactive 3D visualization, but also to support the exchange of annotated data.

Virtual Liver The VIRTUAL LIVER introduced by Crossingham *et al.* [2009] illustrates liver anatomy and typical variants of liver resection. This system provides simple interactions suitable for web-based solutions. As an example, simple labeling techniques are integrated in order to convey anatomical names. A 3D model

4 www.surgerynet.de.

FIGURE e21.6 *The SurgeryNet platform provides entries to educational material for all surgical disciplines. Also links, e.g., related to congresses, live demos and talks are integrated. Like a typical social network, the icons on the right represent the list of professional colleagues.*

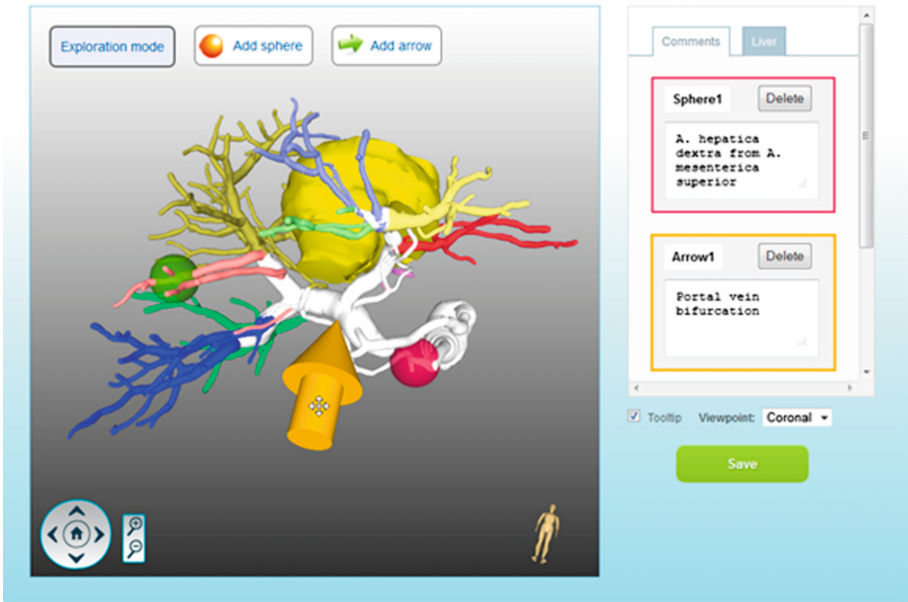

FIGURE e21.7 *In the authoring mode of SurgeryNet, 3D visualizations may be enriched with arrows and spheres to annotate structures (Courtesy of Steven Birr, University of Magdeburg).*

may be rotated in fix steps around fix axes. This constrained and simplified interaction is appropriate in these settings. In general, the whole interaction seems to be very well adapted to the target user group.

However, only one dataset, representing a healthy liver, is provided. Thus, all learning objectives that involve an assessment of the variety of vascular anatomy and spatial relations cannot be achieved. The major web technology used in this system is Adobe Flash.

Webop Webop is a comprehensive system that supports a wide range of learning objectives.[5] It is focused on OR videos using the medium film intensively to convey maneuvers to be carried out during interventions. A large set of such videos is provided representing not only the variability of anatomical situations but also possible differences in operation techniques and tactics including complication management. These videos are annotated and substantial quality control was provided. However, the interactivity is rather limited. Users select videos, may interrupt the presentation and move forward and backward. In contrast, with interactive 3D visualization they could control the camera position and orientation.

A crucial advantage is that videos are integrated in textual chapters that incorporate links to scientific publications and ongoing clinical trials. Moreover, Webop can be used as e-book on a mobile device with the typical multitouch interaction, e.g., to zoom into images or control the videos integrated in the e-book. Webop is described and discussed in detail by Pape-Koehler *et al.* [2010, 2013].

SurgyTec SurgyTec is another comprehensive web-based platform for surgery education providing a large number of videos that document surgical procedures, but also slide shows, full courses and events.[6] Theoretical background knowledge, expert opinions and many case reports are included. Members may also upload content, e.g., inform the community of upcoming events.

WeBSurg WeBSurg refers to itself as the "World Virtual University." It provides a large set of slide shows and streamed presentations related to all aspects of surgery. An editorial team lead by the famous French surgeon Jacques Marescaux and with other experts from IRCAD (Institut de recherche contre les cancers de l'appareil digestif) Strasbourg cares for the high quality of the contributions. According to the pioneering role of IRACD in minimally-invasive surgery and using virtual reality in surgery, the use of new technology is a focus of WeBSurg [Mutter *et al.*, 2011]. Figure e21.8 gives an impression about the organization and content of WeBSurg. Even a collection of whole datasets and derived 3D models is available for download and exploration with a 3D rendering system (Fig. e21.9). Currently, WeBSurg has probably the largest and most diverse community of users. According to [Mutter *et al.*, 2011], the users originate from more than 200 countries.

Discussion There are a number of similarities in the described systems. Pape-Koehler *et al.* [2010] provides a comparison, however, due to the rapid development in this area, not all statements are still valid. Most of the platforms have an editorial board that ensure high-quality contributions but prevents fast updates. These editorial boards act similar to those of journals: they try to acquire contributions contacting opinion leaders and recognized experts for a particular intervention and evaluate the content they provide. A notable difference is the importance of high-quality video material. Thus, most of the platforms described above provide technical assistance to support the acquisition of high-quality videos and the editing process to cut and annotate the raw material.

A common aspect is also that new surgical methods, which are not currently broadly accepted, are slightly overrepresented in these platforms. This is reasonable, since web-based platforms enable faster

5 http://www.webop.de/.
6 http://www.surgytec.com/.

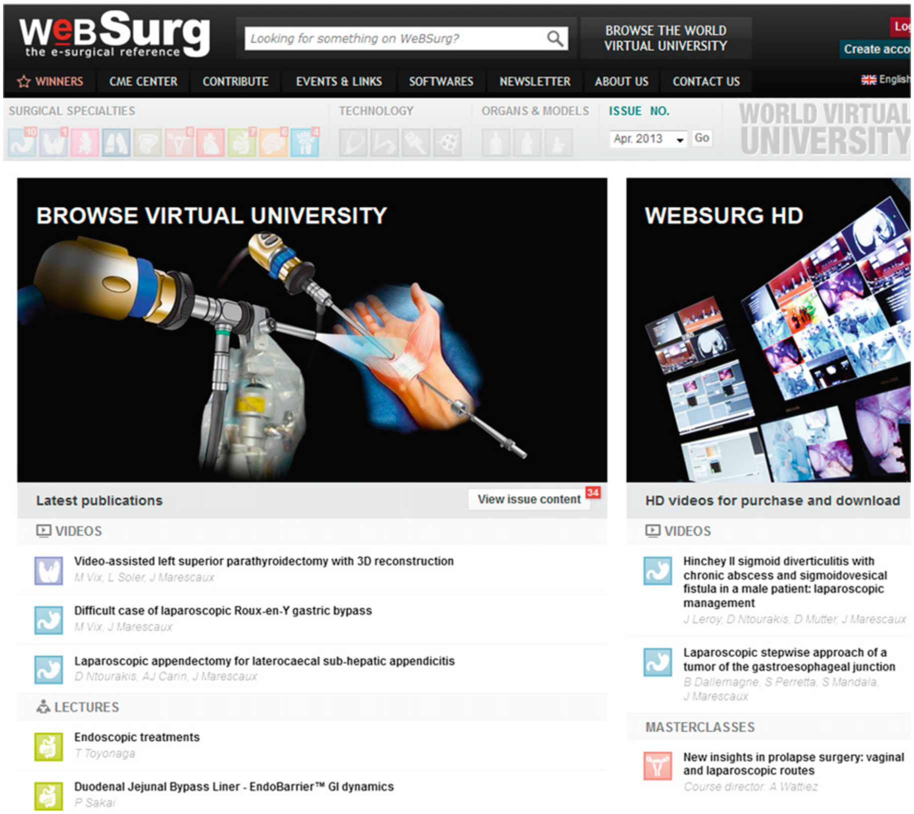

FIGURE e21.8 *A large variety of material is provided by WeBSurg organized according to surgical disciplines, organs, and technologies (Screenshot of WeBSurg).*

distribution of knowledge and thus have an advantage over traditional learning media with their long update periods.

All platforms grow significantly with respect to the content. Thus, the concern raised by Pape-Koehler *et al.* [2010] that web-based platforms are far from providing complete textbook knowledge is probably no longer true. However, it gets more complex to quickly find relevant contributions.

On the other hand, the facilities provided to edit, structure, annotate, and upload the content for such platforms are still complex and difficult to use or too simple in their functionality. Moreover, patient data needs to be very carefully and completely anonymized—this essential process is rarely supported by the platforms. Thus, in contrast to social networks, where many users not only "consume" content, but participate by sharing content, web-based medical education platforms provide content that only a small number of providers have contributed. Thus, there is clear need to improve the tools to provide high-quality content, in particular for anonymization and video editing.

Validation and skills assessment is crucial for all kinds of medical education technology. The most substantial effort so far to assess the effect of using a web-based surgical education site on the skills and relevant knowledge of surgeons is described in Pape-Koehler *et al.* [2013]. They performed a randomized trial that compared multimedia-based training (with WEBOP), with practical training and combined multimedia and

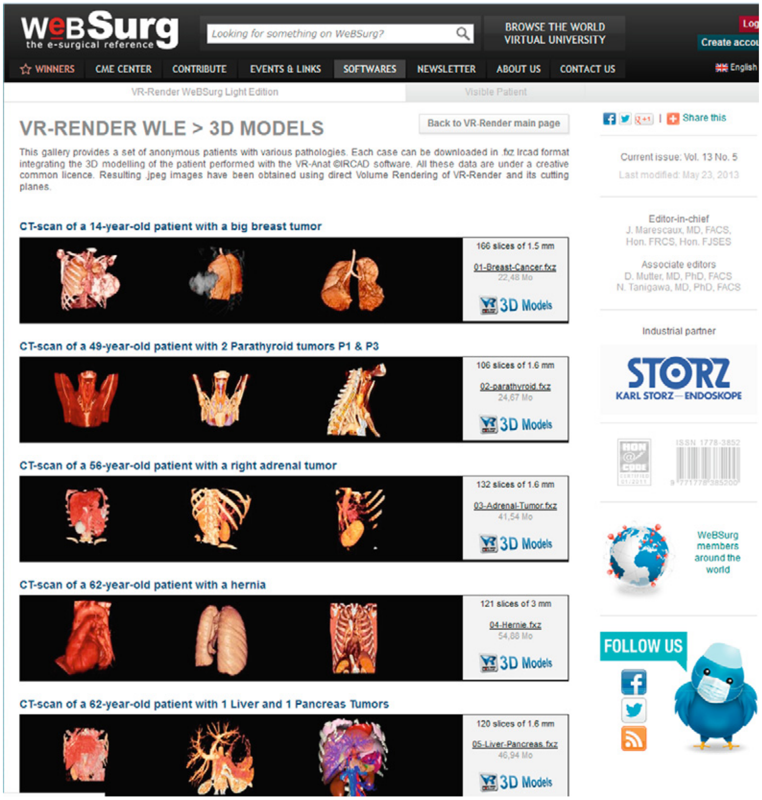

FIGURE e21.9 *Datasets, segmentation information and 3D models are provided for interactive exploration (Screenshot of WeBSurg).*

practical training with respect to laparoscopic cholecystectomy—a frequent minimally-invasive procedure. They could demonstrate a strong effect of multimedia training (compared to no training) evaluating the pre- and post-tests related to 12 relevant aspects of that intervention. The effect on surgical novices was even larger than that of practical training.

All these systems do not focus on image analysis, visualization and interactive exploration of medical image data—the major topics of this book. They are mentioned here, because such web-based platforms represent an essential context for developments in visual computing. Thus, advanced medical visualization may acquire significant influence if properly integrated in these platforms. Of course, these platforms are to support physicians (primarily surgeons). Therefore, only contributions prepared together with medical experts can reasonably be shared with the community.

21.2.5 VISUALIZATION TECHNIQUES FOR MEDICAL EDUCATION

In this chapter, we do not focus on new visualization or image analysis techniques. However, a variety of the techniques presented in the previous chapters are relevant for medical education. Some of them were introduced primarily motivated by use cases from education and training.

Illustrative Rendering In Chapter 12 we learned about low-level and high-level illustration techniques. Low-level illustration techniques enable to emphasize boundaries and other salient features of complex anatomical shapes. High-level illustration techniques adapt the visibility of objects and regions, e.g., by rendering portions of an object transparent or removing it completely. Such illustrative techniques are clearly useful to create expressive renderings of anatomical structures that can be used to *explain* spatial and functional relations.

In contrast to conventional rendering techniques, illustrative rendering techniques provide a significantly more freedom to adjust a visualization to the regions or relations that are important for a particular learning goal.

Enhanced Realism with Texture Mapping To achieve a high degree of realism, and thus to increase trust in training with virtual models, a plausible surface appearance, similar to that of real organs, is advantageous. Texture mapping enables the representation of fine surface detail that is not represented in the explicit surface geometry. Often, intraoperative photos are acquired as a basis for such textures. To actually project a texture on a complex wrinkled anatomical surface without confusing distortions is challenging. Techniques that decompose an organ's geometry, e.g., with polycubes [Tarini *et al.*, 2004], represent a viable option. In a modified version it was used for example to project stippling textures to anatomical structures [Baer *et al.*, 2007] (recall § 12.7).

With these ingredients, anatomy teaching or surgery simulation systems may incorporate surface visualizations where shininess, wetness, or fiber directions of anatomical structures are accurately reflected (see Fig. e21.10). Similarly, textures were extracted and employed for a surgical simulator to train endoscopic interventions. The fine vasculature and the effect of bleeding is represented in a simplified manner by textures (see Fig. e21.11). Kerwin *et al.* [2009] described how a surgery simulator for temporal bone surgery was enhanced with a plausible simulation of wetness effects. The combination of realistic textures and shading significantly adds to the realism of medical education technology.

Labeling Similar to illustrative rendering, also the labeling techniques described in Chapter 10 are primarily motivated by use cases in medical education. To automatically label a set of anatomical structures in 2D or 3D visualizations is essential to get familiar with anatomical names and to relate them to the

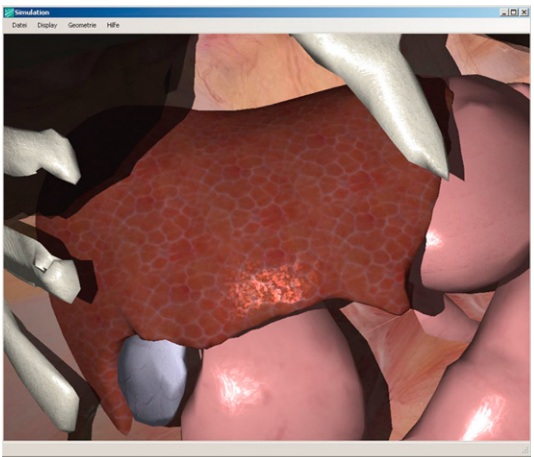

FIGURE e21.10 *The liver is textured based on a digital photo during a laparotomy. Trilinear interpolation is employed to map the texture on the curved liver surface. These models are used for a surgical simulation system (Courtesy of Simon Adler, Fraunhofer IFF Magdeburg).*

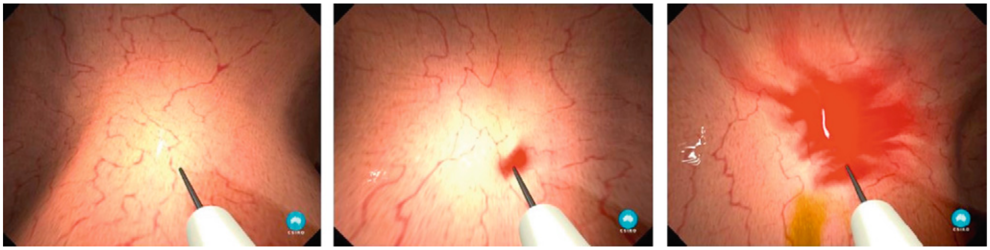

FIGURE e21.11 *Incorporating realistic textures in a endoscopic surgery simulation system (Courtesy of Christoph Russ, Australian E-Health Research Centre, CSIRO).*

corresponding shapes. While in radiology reports often only a single structure is annotated and labeled, for educational purposes it is often necessary to present a number of labels simultaneously. This gives rise to more advanced algorithms to place internal or external labels that avoid intersecting lines and obscuring relevant image regions.

Animating Medical Visualizations As a final family of visualization techniques relevant for educational systems we briefly discuss *animation*, a topic that was not introduced in any of the previous chapters.

Animations may effectively convey complex spatial relations between anatomical objects. As an example, a large series of educational animations was generated in the DIGITAL ANATOMIST project (see § 21.3). Animations may also be used to convey

- different stages of development, e.g., growth processes,
- functional information, such as the range of motion of joints, and
- transportation, e.g., of cells that react on an attack to the immune system.

Thus, animations can convey the dynamics of pathological and physiological processes. A clear time frame is useful in these use cases [Brenton *et al.*, 2007].

Compared to static illustrations, animations offer additional degrees of freedom to emphasize objects and to clarify their spatial configuration by performing gradual frame-to-frame changes. The observation of gradual changes between visualizations is mentally easier compared to the interpretation of two static images. The space of meaningful animation techniques depends on the data and derived information. Most anatomy education as well as surgical education systems are based on medical volume data and derived segmentation information. Typical animation techniques include the rotation of the whole dataset, zooming toward relevant structures, the movement of clipping planes, the movement of the camera along a certain path, for example through tubular structures, and gradual changes of the transparencies of objects. The design of animations that are successful in educational settings should consider findings from perceptual psychology. As an example, the number of movements that take place simultaneously should be limited [Tversky *et al.*, 2002].

These drawbacks gave rise to the development of script-based specification methods for animation design. These animation systems employ *decomposition rules*, which define the mapping of high-level specifications to low-level commands. A first attempt to generate dedicated animations of medical volume data is described in [Mühler *et al.*, 2006]. This scripting language supports slice-based visualizations and movements of clipping planes. It can be tailored to clinical tasks, such as evaluating the infiltration of a risk structure by a tumor or evaluating the resectability of a tumor patient. Default techniques to emphasize different categories of anatomical structures are employed. As an example, a camera movement along an object's centerline is appropriate for elongated objects, such as vascular structures. Later, the animation authoring was further enhanced by incorporating components that support the *re-use* of animations for similar datasets [Mühler and Preim, 2010].

Animations are widely used in medical education systems. As an example, the DigitalAnatomist (§ 21.3.2) provides a large set of animations. In these animations, objects are incrementally included, rotated, zoomed, exploded (outer objects are moved away), and finally labeled.

21.3 ANATOMY EDUCATION

In the following, we briefly describe computer support for anatomy education. We emphasized the importance of a careful user and task analysis for developing medical education systems. With respect to anatomy education, Brenton *et al.* [2007] and Jastrow and Hollinderbäumer [2004] discuss that the mental ability to understand anatomical structures as 3D objects is very important and hardly supported by other modes of education. Therefore, we restrict the discussion to systems which employ 3D models instead of scanned drawings. Keyword searches and high-quality images were also mentioned as important features desired by medical students.

Our discussion is focused on middle- and long-term projects systems carried out at research institutions since these are documented well in the literature. We start this section with the VoxelMan—the pioneering 3D anatomy teaching system.

21.3.1 VOXELMAN

The first version of the VoxelMan was based on a labeled MRI head dataset [Höhne *et al.*, 1992]. The system supports a flexible exploration of the data, labeling of anatomical structures as well as the inquiry of a sophisticated knowledge base (recall § 21.2.2). The knowledge base is employed to "interrogate" the graphical representation using context-sensitive pop-up menus. Direct volume rendering was employed for 3D visualization, which was unusual at that time due to the high demands for system performance.

The second generation of the VoxelMan supports regional, systematic, and radiographic anatomy based on the Visible Human dataset and segmentation information as well as an advanced knowledge base. 650 anatomical constituents as well as 2000 relations between them are represented in the knowledge base [Pommert *et al.*, 2001]. The VoxelMan provides many interaction facilities to explore the Visible Human data and the correspondence between the different datasets. Clipping and cutting facilities are included to virtually dissect the patient. For example, a clipping plane may be moved through a 3D volume-rendered image and simultaneously corresponding slices of CT and photographic data are shown. X-ray images may be simulated (as an average projection of the CT data, Fig. e21.12, left) and cross sections of CT data can be integrated with 3D surface renderings (Fig. e21.12, right).

21.3.2 DIGITALANATOMIST

The DigitalAnatomist is a long-term project, carried out at the Structural Informatics Group of the Department of Biological Structure at the University of Washington. The knowledge base underlying the system is huge. Already in 1999, 26,000 anatomical concepts and 28,000 semantic links were represented [Brinkley *et al.*, 1999]. The links are explored with a hypertext functionality; the represented relations are very similar to those used in the VoxelMan (recall Fig. e21.5 and § 21.3.1). Labeled histologic image data based on tissue samples are available.

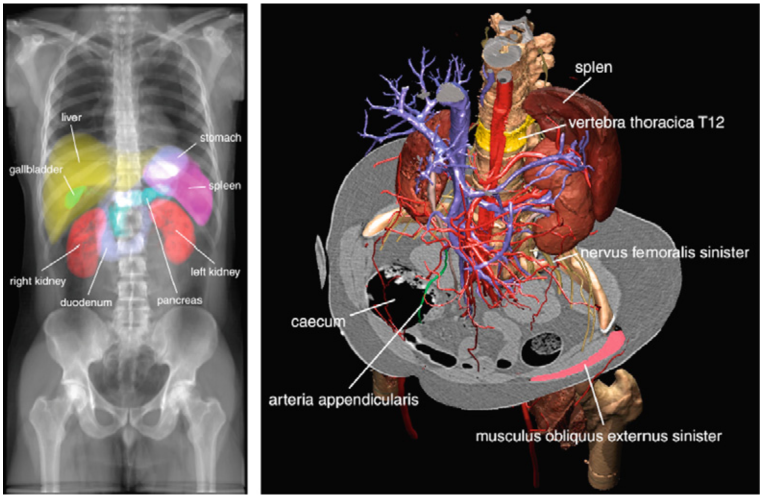

FIGURE e21.12 *Different viewing modes used in the* VoxelMan. **Left:** *simulated X-ray.* **Right:** *CT slices combined with surface rendering of selected objects (From: [Pommert et al., 2001]).*

The DigitalAnatomist contains a quiz where people can select objects and enter their names, as a simple kind of self-assessment. In some animations, vascular structures grow along a path. Often, structures are clipped to reveal the insights. All drawings can be modified by adding outlines and labels. The system may be used in different modes, for examples as a tutorial or in a question-and-answer mode. The interaction facilities to explore the 3D models, however, are limited.

The DigitalAnatomist is available as web platform.[7] The project was finished in 2008 and thus does not make use of any recent web technology.

21.3.3 ANATOMYBROWSER

The AnatomyBrowser, developed at the Brigham and Womens Hospital in Boston, is also a comprehensive system representing a wealth of anatomical relations [Kikinis et al., 1996a]. It was probably the first system available on standard PCs and later as web-service based on Java. The focus of the AnatomyBrowser is also on neuroanatomy. Labeled MRI data have been used as major data source for the system. Since a variety of datasets, in particular of the brain, is included, comparative anatomy can be explored. The comprehensive knowledge base enables a flexible exploration. The AnatomyBrowser project was finished in 2003, but the system is still available.[8]

21.3.4 PRIMAL PICTURES

In addition to the systems and concepts discussed in the scientific literature, also a commercial entity should be mentioned: Primal pictures[9] presents a well-known suite of anatomy education tools. The next generation of anatomy education tools will likely incorporate realistic movements and functional information, for example with respect to blood flow and metabolism. Anatomy education tools may also be extended to

7 http://www9.biostr.washington.edu/da.html.
8 http://www.spl.harvard.edu/archive/spl-pre2007/pages/papers/AnatomyBrowser/current/.
9 see http://www.primalpictures.com/.

provide case studies of pathologies. Primal pictures also provide large sets of interactive 3D visualizations which present important sports injuries.

21.3.5 ZYGOTE BODY

This recently introduced tool is based on a substantial analysis of the current situation in anatomy teaching and the potential and necessity for computer support [Kelc, 2012]. It employs recent Web3D technology and received very good feedback in a user study with 73 users. An interesting aspect of the evaluation relates to the question which anatomical structures users found most interesting. It turned out that muscles were considered primarily interesting, because they have a complex structure that is not easy to understand and they are represented well in the 3D models. Structures of the central or peripheral nervous system, on the other hand, are very small and difficult to fully understand.

21.3.6 BIODIGITAL HUMAN

BioDigital Human is another recent development that already gained considerable acceptance. It provides intuitive interaction with 3D visualizations of the anatomy, but moreover conveys a number of animations revealing physiology. Thus, users may watch the beating heart and dissect it virtually. A model of atrial fibrillation is included and devices, such as implants, may be integrated. Thus, BioDigital Human actually provides more than anatomy knowledge. The system is described in [Qualter *et al.*, 2012], but it is recommended to watch the set of videos available at YouTube to fully appreciate the interactive technology.

21.3.7 LiverAnatomyExplorer

In contrast to the previously described systems, the LiverAnatomyExplorer was developed recently and employs rather new web-based technology [Birr *et al.*, 2013]. It has a clear focus on liver anatomy, in particular the variability of vascular supply and drainage should be conveyed. Thus, the LiverAnatomyExplorer employs case data that was extracted from contrast-enhanced abdominal CT data. Important variants of the vascular anatomy were identified primarily because their occurrence determines surgical decisions (§ 21.4.2). In addition to the learning module, there is a prototypic authoring component where tasks and solutions may be assigned to individual cases. This authoring component is carefully designed: users are strictly guided by a wizard in the process of uploading, structuring, and editing the material.

The requirement analysis among 176 students and 13 physicians revealed enthusiasm about web-based teaching, also among the physicians from which most were engaged in teaching activities. However, very few students and only a minority of physicians consider themselves as familiar with interactive 3D visualization. Thus, to avoid navigation problems in 3D content and to enable intuitive interaction has high priority.

Technical Concept All geometric models are derived from medical image data (high resolution CT angiography). A variety of segmentation techniques was used to create binary segmentation masks of all relevant structures. The raw surfaces representing the segmentation results were simplified and smoothed (reducing in a file size that was an order of magnitude smaller than before this step). The files were converted to X3D and used in a X3DOM wrapper application (Fig. e21.13).

For a web-based educational system, the performance is a crucial issue and more important than a very high accuracy. Thus, after segmentation, results may be represented in a lossy jpeg compression. Segmentation results are presented as overlays that are stored as SVG files (see Fig. e21.13). SVG, scalable vector graphics, is appropriate, since the amount of data is reduced and the visual quality, e.g., after scaling the viewer, is better than in a pixel-oriented file format. More precisely, the Raphael SVG framework

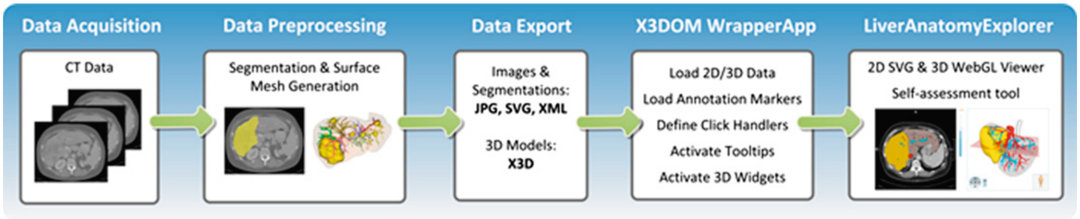

FIGURE e21.13 *Data processing for a web-based educational system includes image segmentation and transformation to formats that are suitable for web-based viewing. The actual educational system is built on top of a wrapper application based on WebGL and X3DOM (From: [Birr et al., 2013]).*

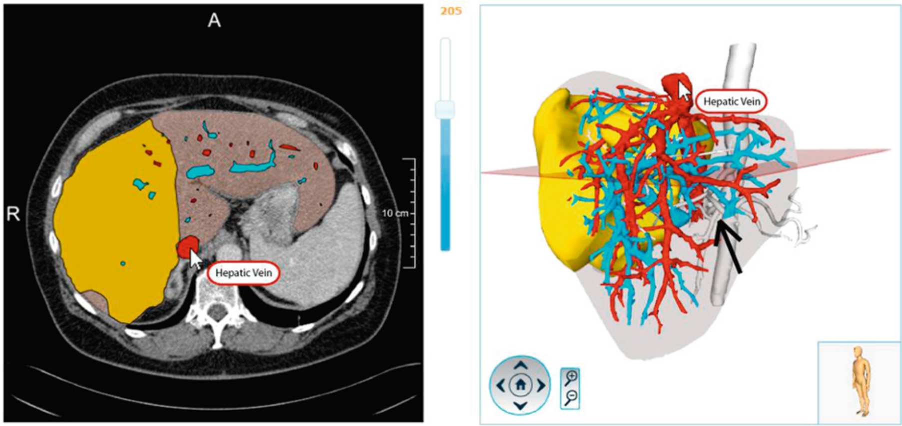

FIGURE e21.14 **Left:** *In the 2D slice view, segmentation information is presented as colored overlay. The hepatic vein is temporarily labeled after the trainee moved the cursor of its region.* **Right:** *Also in the 3D view the hepatic vein is labeled. Rotation and zooming is performed by means of the widgets placed on top of the viewer. A mannequin is integrated as orientation widget to convey the current viewing direction (From: [Birr et al., 2013]).*

along with JavaScript is employed to realize a plugin-free 2D slice viewer (Fig. e21.14, left). A very useful function is to enhance selected objects and to present labels temporarily.

XML is used to represent and label the various segmentation results. As a prerequisite for interactive 3D viewing, geometric 3D models are stored as X3D files. The X3D files have a size of 5–10 Mbytes and can be rendered in real-time (20–25 fps) with a modern graphics card.

Although the content and the specific didactic concept is focused on liver anatomy, the whole technical concept can be re-used for any other type of educational system based on medical volume data.

User Interface Design The cases are presented in 2D and 3D viewers developed on the basis of WebGL and X3D. Users can interrogate the visualizations by moving the cursor over an interesting region and getting context-sensitive information in a tooltip. Interactive 3D viewing is possible and synchronized with the 2D view, e.g., in case of selections (Fig. e21.14). A 3D widget, inspired by Google Maps, was developed to enable stepwise rotation (30° per step) and zooming. The transitions are realized continuously by interpolating between the viewpoints to avoid sudden and confusing changes.

The LiverAnatomyExplorer also enables self-assessment. In this mode, trainees are asked, e.g., whether or not a certain vascular abnormality occurs. This is an essential task for both radiologists and surgeons. The presence of abnormalities should be stated in a diagnostic report, but in case it is missed, also the surgeon should be able to recognize it. Further tasks relate to the vascular supply, e.g., "select the portal vein branch that supplies segment five."

Evaluation A user study with 54 trainees was performed. The trainees were students of medicine (40 females, average age 24 years). After a tutorial, students used the system to explore the data and to answer quiz-like questions, which was mandatory to get further cases. After the test, a questionnaire with 14 questions was filled on a 5-point Likert scale and verbal comments were also collected. Eight questions related to user interface issues and six to the perceived learning effort. The answers to all user interface questions were—with one exception—above average with the highest values for the self-explanatory nature, the fast performance and the overall design. The answers with respect to the perceived learning effect were also on average above the neutral value (3), but lower than for the user interface-related questions. The feedback for learning and the overall learning success were assessed with 3.5. The lowest value (2.8) was found for the learning questions which turned out to be partially too difficult for students.

Verbal comments revealed that the mannequin used as orientation cue was highly welcome. The selection of small or thin structures, that is sometimes necessary to answer questions, was considered as a problem. Interestingly, the evaluation of the Zygote Body revealed the same problem [Kelc, 2012]. More advanced 3D selection techniques, including smart snapping strategies, were discussed in § 5.6.1. The evaluation of Zygote Body also revealed that often multiple 3D objects need to be selected or deselected and that a careful analysis is necessary to provide adequate support in all these situations, e.g., by enabling flexible grouping of objects.

21.3.8 DISCUSSION

Substantial progress in computer-supported anatomy education was achieved in recent years due to the availability of high resolution data, strongly improved (graphics) hardware, standards for web-based viewing as well as increasing awareness of essential didactic concepts. The complex systems described by Brenton *et al.* [2007] in highly interdisciplinary cooperations are showcase examples indicating the potential of computer support.

However, significant further development is necessary. Conceptually, this relates to a better integration into curricula, comprehensive studies and their documentation to assess learning effort and acceptance. Among few systems that not only provide substantial features to learn various aspects of anatomy, but also to support in-depth evaluation, belongs the work of Temkin *et al.* [2006].

Technologically, in particular user interface issues are essential to significantly reduce the need for cadaver dissection. For this purpose, students should be able to "feel" the anatomy. Force feedback and more intuitive 3D input should replace simple mouse-based interaction. We later discuss haptics for surgery simulation where this is used more extensively. More dynamics, e.g., visualizations of contractions and articulations of muscles are also essential features for future systems. Finally, collaboration should be better supported, e.g., with modern tabletop systems.

21.4 SURGERY EDUCATION

The design of e-learning systems for surgery has to consider the different constituents of surgery education [Mehrabi *et al.*, 2000].

- *Surgical theory* relates to factual knowledge as a basis for decision-making processes.

- *Clinical surgery* is based on surgical theory and comprises pathological variations, differential diagnosis, and therapeutic alternatives. In clinical surgery, students should critically reflect on the solution of surgical problems.
- The study of *operative techniques* is based on knowledge in the former areas and aims at skills development.

While Mehrabi *et al.* [2000] focused on surgery, a very similar discrimination is relevant for interventional radiology, where, e.g., a clot in a vascular structure is removed with a catheter. This intervention also requires similar theoretical knowledge and finally skills with respect to maneuvering a flexible catheter in vascular structures.

A related, but somewhat different classification is presented by Waxberg *et al.* [2004]. They regard the acquisition of surgical skills as a special instance of the general process of the acquisition of motor skills. This process consists of three stages:

- *a cognitive phase* where a novice becomes familiar with the process to be performed and learns how to attempt first trials,
- *the associative phase* where the subject learns to perform the skill and which teaches subtle adjustments, and
- *the autonomous phase* which begins after several months of practice and relates to the time when the skill can be performed largely automatically.

In § 21.4.2, we briefly review systems for studying surgical theory and clinical surgery and discuss one of them, dedicated to liver surgery, in more detail.

Most research on surgery education and simulation was carried out with respect to the study of operative techniques. Surgery simulators have been developed, e.g., to simulate the behavior of soft tissue or the drilling of skeletal structures, the interaction of surgical devices with soft tissue as well as different surgical techniques, secondary effects and complications. A brief review of these systems and the challenging tasks that have to be solved is given in § 21.7. With respect to the stages described above, such systems support the *associative phase*, often without supporting the cognitive phase.

e-learning Systems for Studying Clinical Surgery The potential and necessity of e-learning systems for surgery education was recognized early [Klar and Bayer, 1990]. e-learning systems for clinical surgery are necessary in order to cope with the rapid growth of relevant knowledge in the surgical disciplines [Mehrabi *et al.*, 2000]. Meanwhile, in many countries surgery simulation is also discussed as a means toward more effective and more standardized education. Due to the shortage of experienced surgeons, these experts do not have sufficient time for educational activities.

In the following, we describe two exemplary systems where the interaction with medical image data plays an essential role. The conceptual design of both systems is based on the *four-component-instructional-design model* [van Merriënboer *et al.*, 2002]. This model was selected, since it is focused on the transfer of procedural knowledge. Thus, problem-solving strategies should be improved instead of acquiring factual knowledge.

The model suggests the emphasis of subtasks that may be critical (due to the involved risk). Moreover, the arrangement of training cases into simple, moderately difficult and difficult cases is suggested. The amount of information and guidance provided by an educational system should be adapted to these different levels of difficulty. Finally, supportive information should be presented just in time (that is, when they are actually needed).

21.4.1 COGNITIVE TASK ANALYSIS FOR SURGERY AND INTERVENTIONAL TRAINING SYSTEMS

The task analysis that is necessary as a basis for designing training systems is challenging and needs to include a deep understanding of the relevant procedures. Classical techniques, such as observation of a few procedures, recording the sequence of actions and eventually supported by short interviews to prepare a *workflow description*, are a basis, but not sufficient. Experienced surgeons and interventional radiologists perform procedures with a very high level of automation, like an experienced piano player. They are not aware of most of their decisions, since they are carried out unconsciously. When asked about their approach, they can usually not fully explain why they chose a particular instrument, a particular access strategy, or why they avoided alternatives.

Cognitive task analysis is an in-depth task analysis that is usually performed by psychologists that made themselves familiar with the task to the extent of a trainee. In surgery this means, that he or she knows the basic approach, the role of all team members, the essential instruments and their importance in surgery as well as the basic workflow. Cognitive task analysis is based on several observations followed by in-depth interviews with multiple experts to discuss observations to reveal this hidden or implicit knowledge. Video recordings in order to repeatedly observe and analyze the handling are essential.

An inspiring and substantial effort has been made by Johnson *et al.* [2006] to perform a cognitive task analysis for interventional radiology. It was focused on five frequent procedures, such as arterial palpation and ultrasound-guided biopsy. As an example, arterial needle puncture is characterized as a process with 101 steps and 24 decision points, summarized in a 20 page document. These and similar descriptions are available at the website of CRaiVe (Collaborator in Radiological Interventional Virtual Environments).[10] Cognitive task analysis has also been used for informing the design of surgical training, see e.g., [Campbell *et al.*, 2011].

21.4.2 LIVERSURGERYTRAINER

The LIVERSURGERYTRAINER contains cases of patients with liver tumors that are presented with a wealth of information comprising the anamnesis and initial diagnosis, radiologic diagnosis, and image analysis results. Therapeutic decisions, such as resectability and resection strategy, can be trained. Expert opinions are integrated and used to provide feedback to the learning surgeon. The system uses planning functionalities, e.g., virtual resection (see Fig. e21.15). In particular intraoperative video sequences are employed to show how the planned resection was actually performed. In cooperation with experienced surgeons, learning objectives and more elementary goals are determined. Based on this discussion, the LIVERSURGERYTRAINER provides a *workflow*, starting from the anamnesis and diagnosis. Operability (based on clinical parameters) and resectability (based on the individual liver anatomy) should be evaluated based on the patient's anatomy. Figure e21.16 shows the start screen that gives an overview of the available steps.

A comprehensive overview of the LIVERSURGERYTRAINER is given in [Mönch *et al.*, 2013].

Medical Background We briefly explained the vascular anatomy of the liver in § 21.3.7. Thus, here we focus on tumor surgery and living donor liver transplants.

Living donor liver transplants (LDLT) are motivated by the shortage of donor organs for patients with severe and progressive liver disease. The liver of a healthy volunteer donor is split in a way that the donor can live with the remaining portion and the receiver with the resected part. LDLT is possible since the liver regenerates, that is, after surgery it grows until it reaches almost its original size after a few month. LDLT surgery is very demanding, since the whole liver needs to be split and the vascular supply and drainage

10 http://www.hpv.cs.bangor.ac.uk/CRaIVE/projects.php.

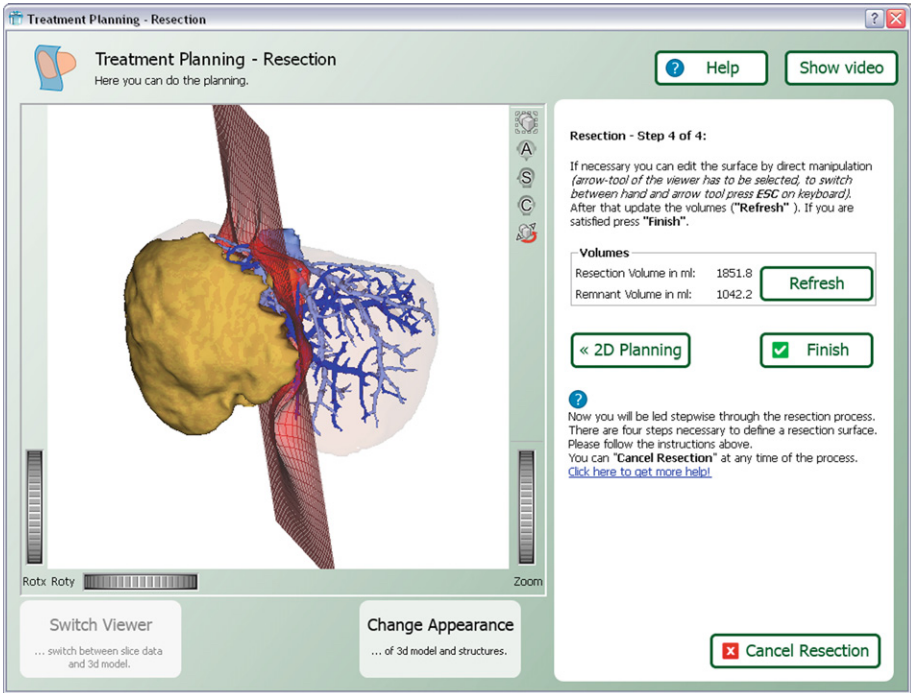

FIGURE e21.15 *The LiverSurgeryTrainer provides support for therapy decisions in oncologic liver surgery. A predefined workflow guides the trainee through the environment. In the current step, the resection should be planned. Later, the user can observe several sequences of an annotated intraoperative video (Courtesy of Konrad Mühler, University of Magdeburg).*

as well as the bile duct supply needs to be ensured for both the donor and the receiver. An understanding of vascular abnormalities is of paramount importance to understand whether or not a potential donor is indeed suitable.

In case of hepatic carcinoma or hepatic metastasis from colorectal cancer, surgical removal of all tumors has the best prognosis. However, this good prognosis requires that all tumors are removed with a sufficient safety margin. Thus, patients with further metastasis in other organs do not benefit, since in this systemic stage no local treatment can significantly improve survival rates. Complete surgical removal is only possible

- if the patient's general state allows a complex surgery,
- if the liver function is not severely hampered, e.g., by a late-stage cirrhosis, and
- if sufficient functional liver volume remains after surgery.

There are various typical resections that differ in their extent:

1. a *hemihepatectomy* (removal of right or left lobe of the liver),
2. an *extended hemihepatectomy* (removal of right or left lobe of the liver and additional segments), and
3. a *central resection* (removal of central/middle segments)

In addition, there are so-called non-anatomical resections, e.g., a wedge resection where a peripheral tumor with a safety margin is removed without further consideration of vascular supply areas. As in

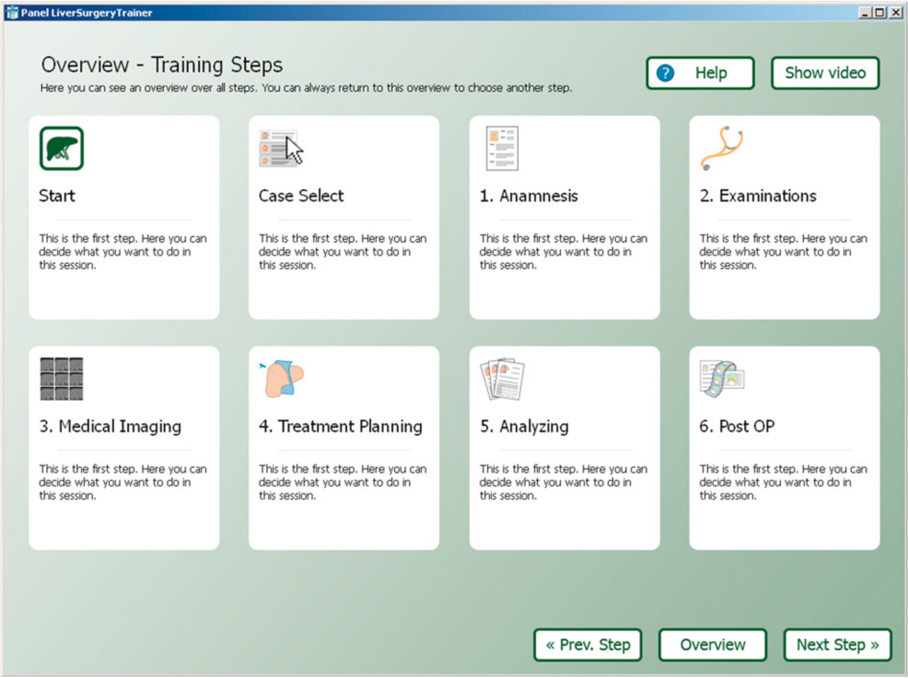

FIGURE e21.16 *The graphically oriented overview of the LiverSurgeryTrainer (Courtesy of Konrad Mühler, University of Magdeburg).*

clinical practice, training is based on bi- or triphasic contrast-enhanced CT data and derived segmentation information. In addition, clinical information is provided, e.g., to assess the severity of a cirrhosis.

Learning Objectives At a high level, the learning objectives may be specified as follows. Assistant doctors should be able to

- assess the resectability of a patient,
- determine the extent of a resection,
- plan the resection in detail, e.g., with respect to the portal vein, the hepatic artery and the veins.

These rather high-level goals require that assistant doctors know the decomposition of the liver in functional units, the so-called liver segments, the vascular structures (portal vein, hepatic vein, hepatic artery, and bile ducts) as well as their typical variants (recall § 21.3.7).

The role of the safety margin in tumor surgery is discussed in [Pawlik *et al.*, 2005]. Fischer *et al.* [2007] have shown that computer-assisted planning enhances surgical outcomes. The classification of different degrees of difficulty is also based on research in surgery, e.g., the work of Beller *et al.* [2009]. The training of LDLT cases is based on experiences in LDLT planning and donor evaluation [Radtke *et al.*, 2007].

Case Database The selection of cases and the enrichment of the image data with segmentation, planning information, such as safety margins and tumor volume, textual annotation, and expert suggestions is essential. The LiverSurgeryTrainer provides 16 cases, two of them for training decisions related to living donor liver transplants and 14 for tumor surgery. Surgical experts classified these 14 cases in three levels of difficulty (2 difficult, 7 moderately difficult, 5 easy cases). The classification of cases also considers vascular abnormalities (recall § 21.3.7). Cases with central tumor, metastases in both liver lobes and with associated severe cirrhosis are classified as more difficult, whereas easy cases contain smaller tumors in peripheral regions. The level of difficulty is the most important attribute presented to the trainees for the selection of a training case. Other essential information, such as age, gender, and major diagnosis, is also provided. A weakness of the case database is that all cases are actually resectable. Thus, the LiverSurgeryTrainer cannot illustrate why certain patients are not eligible to surgery.

According to the defined workflow, trainees should select a case, deal with the diagnostic results and perform resection planning before their result is analyzed (see Fig. e21.17).

In addition to all relevant information that is provided preoperatively, selected intraoperative views and videos are provided (Fig. e21.18). Moreover, the documented resected tissue (Fig. e21.19) is also shown to illustrate whether surgical removal was possible as intended.

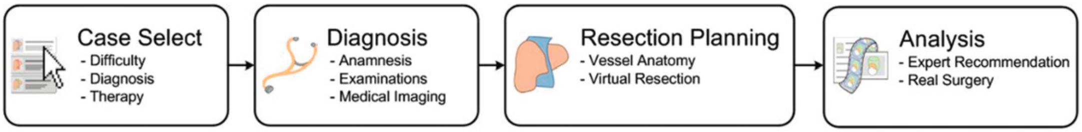

FIGURE e21.17 *Workflow supported by the LiverSurgeryTrainer. Resection planning is the core component with a number of subcomponents including 2D and 3D visualizations (Courtesy of Konrad Mühler, University of Magdeburg).*

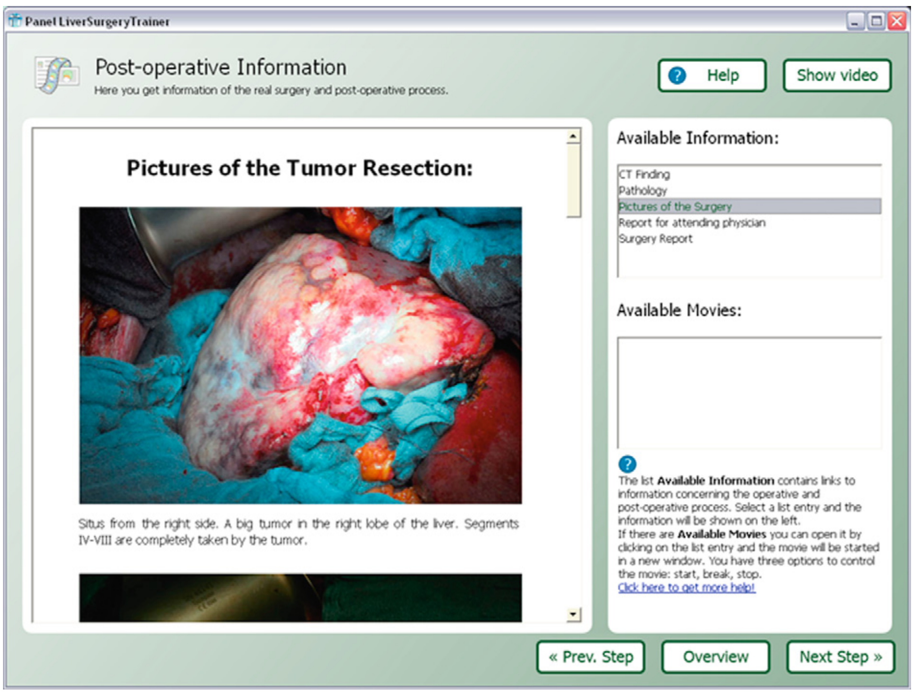

FIGURE e21.18 *Intraoperative views are provided in order to assess how the planned intervention was actually performed (Courtesy of Karl Oldhafer, General Hospital Celle).*

FIGURE e21.19 *The removed tumor (white tissue) is completely surrounded by liver tissue. However, the safety margin is rather small at the top of the tumor (Courtesy of Karl Oldhafer, General Hospital Celle).*

User Interface Design The whole design process was guided by a discussion of scenarios (recall § 5.2.3.2) and in later stages by feedback during evaluations of the system. Scenarios in particular helped to determine which cases are essential and how these cases should be used to enable trainees to get relevant experience with respect to the learning objectives.

Initial versions of the LiverSurgeryTrainer were criticized as being too complex with respect to the number of interface controls in each step. Thus, the design was optimized by decomposing complex actions into simpler steps, providing clear guidance, and by removing interface controls that were rarely needed, or by hiding them in "advanced options" panels.

Another essential impression from user feedback is that users expect an attractive visual design—a good user experience (recall § 5.5.3). Thus, instead of textually labeled buttons, visual representations were carefully designed. As a consequence, most panels contain a few large, primarily visual interface controls instead of many textual components (see Fig. e21.20 for examples).

Expert Feedback Adequate and reproducible expert feedback is a crucial component of e-learning systems in general. In the case of operative medicine, there is not *one* correct solution, but different feasible strategies. A solution is criticized when it violates essential guidelines, e.g., the safety margin is too low or the risk for a vital structure too high. The strategies actually used by experts depend on their own experience, but also on their *surgical school*. To reflect this aspect, two resection proposals from two experts are presented for each case. Of course, there are more viable strategies in most cases, but two proposals also invoke a careful thinking about alternatives.

A crucial question is how to present an expert resection strategy and how to enable a comparison of the trainee's strategy with the expert strategy. The resection strategy is represented in a resection shape. The trainee may compare his or her resection strategy with that of an expert as a side-by-side comparison with synchronized viewers (that is, zooming and rotation is performed simultaneously in both viewers, see Fig. e21.21). In the same way, also the two expert proposals may be compared. The simultaneous display of all three resections was considered inappropriate, since resections are rather complex and there is neither enough space at a typical screen, nor it is convenient to compare three complex shapes simultaneously.

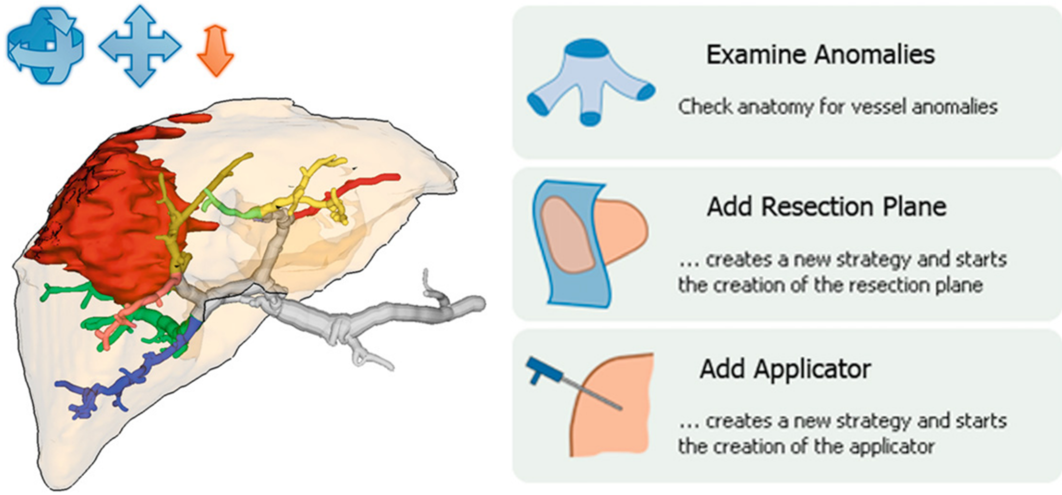

FIGURE e21.20 **Left:** Incremental 3D interaction with appropriate buttons is less flexible but easier to control and better suited for the target user group. **Right:** For all steps, a carefully designed icon is provided (Courtesy of Konrad Mühler, University of Magdeburg).

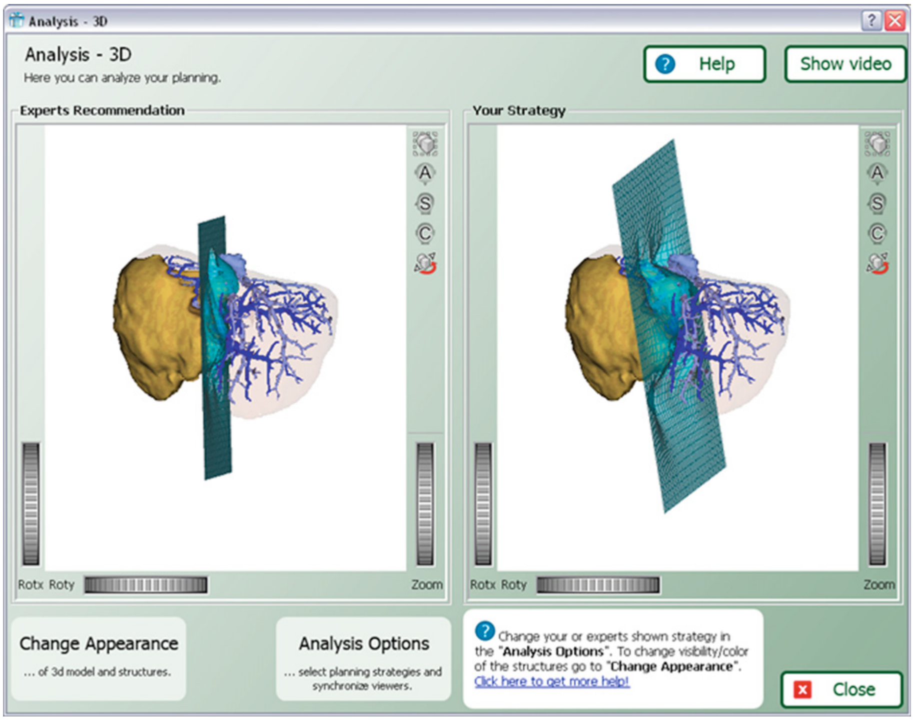

FIGURE e21.21 The resection proposal performed by an expert and by a trainee are compared in synchronized 3D viewers (Courtesy of Konrad Mühler, University of Magdeburg).

The resection proposal is also quantitatively analyzed, e.g., with respect to volume and remnant volume as well as the safety margin. All these visualizations and analysis results, of course, do not reveal *why* the expert chose this strategy. Therefore, each resection strategy also contains a verbal comment.

Evaluation The evaluation is aimed at usability, user experience, and the learning effect. Twelve surgeons participated in the evaluation, representing a wide range of professional experience (six of them with more than 5 years). All surgeons were male and aged between 27 and 63. The specific results are discussed by Mönch *et al.* [2013]. In summary, the substantial redesign was appreciated by the test persons (the same persons participated in an earlier study). In particular the general impression, and the ease of learning were considered as significantly improved.

In addition, the perceived learning experience was explored. At least a certain level of usability is a prerequisite for a good learning experience, but other aspects, such as the didactic concept, the quality and structure of the content and its specific presentation are essential as well. The impression of trainees strongly depends on whether the system is designed for the "right" audience and supports tasks that are considered as relevant in practice. Four medical students and two assistant doctors took part in that evaluation—a number that is too small for any definitive results. The trend, however, indicates that test persons improved their understanding of the planning workflow, the abilities to explore the 3D models and to virtually resect patients [Mönch *et al.*, 2013]. Thus, they will likely be able to use complex planning tools. It remains to be evaluated how such a training improves other skills relevant for clinical practice.

21.4.3 SpineSurgeryTrainer

In the following, we describe an additional system for clinical surgery using the same structure as we employed before for the LiverSurgeryTrainer. This system, the SpineSurgeryTrainer, is dedicated to minimally-invasive spine surgery, an intervention that becomes necessary in case of persisting and severe prolapse. Compared to the previous system, this description is significantly shorter for two reasons. First, we describe this system just as a second example to illustrate general concepts for the design and evaluation of systems for supporting clinical surgery. Second, the development of the SpineSurgeryTrainer was a rather small project, leading to a proof-of-concept instead of a fully functioning prototype ready for widespread use. The system is described by Cordes *et al.* [2008] and Kellermann *et al.* [2011].

Medical Background The focus of the SpineSurgeryTrainer is orthopedic spine surgery [Oppenheimer *et al.*, 2009]. In contrast to open surgery where the surrounding anatomy is directly visible, minimally-invasive surgery is more demanding for the surgeon due to the limited and indirect vision. The anatomy around the spine contains vulnerable structures, such as the spinal cord, vessels, and nerves that should not be hurt. On the other hand, access is limited by impenetrable vertebrae. Therefore, surgical training systems are particularly important for minimally-invasive needle-based interventions. An essential needle-based intervention is *lumbar puncture*, where the cerebrospinal fluid inside the spinal canal is extracted with a biopsy needle for diagnostic purposes. Anatomical landmarks, such as the dorsal process and iliac crest, are found by palpation and guide needle placement. While we discuss in the following how the anatomy is displayed and treatment decisions are trained, we later (§ 21.6.3) discuss a training that also involves the dexterity needed for performing needle-based interventions.

Treatment decisions are based on radiological diagnosis, neurologically disturbed functions, discomforts reported by the patient as well as social aspects, since the occurrence and severity of back pain is known to be related to social factors, such as employment status and psychological stress. The spatial relation between nerval and spinal structures as well as the location of the spine in relation to surrounding muscles and vascular structures has to be considered [Cordes *et al.*, 2008]. While access from the back

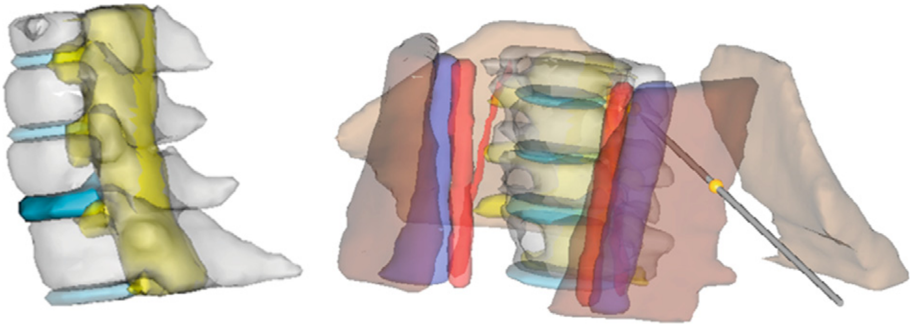

FIGURE e21.22 **Left:** *The anatomy of the spine.* **Right:** *The spine and its surrounding anatomy where a needle needs to be carefully maneuvered to avoid damage to crucial structures (Courtesy of Kathrin Hintz, University of Magdeburg).*

is by far easier, since only very few structures are encountered, it may be impossible due to the specific location of the pathology. Figure e21.22 illustrates the relation between the needle and crucial anatomical structures. In particular, herniated disks in the cervical region often require frontal access (along a variety of essential structures in the neck). But even in this region, sometimes the (easier) access from the back is possible and should be chosen in these cases.

Learning Objectives Using the SpineSurgeryTrainer, trainees should reinforce their relevant anatomical knowledge (on top of the assumed basic knowledge). In addition, they should learn how

- to decide on an effective therapy,
- to access the pathology (see Fig. e21.23),
- small variations of the position and orientation of the affected vertebral influence the decision with respect to the access.

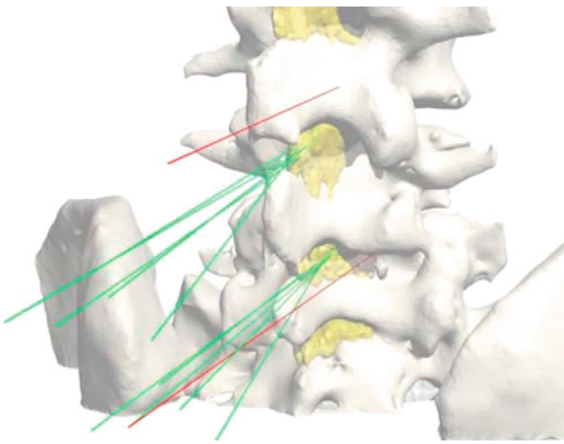

FIGURE e21.23 *Possible (green) and impossible (red) needle placement in the cervical spine. To get an intuitive understanding of possible needle angulation and placement is an essential learning goal in spine surgery training (Courtesy of Mathias Färber, University of Lübeck).*

These rather high-level goals require that trainees know the relevant anatomy. In particular if a ventral access path is required, the needle has to pass a variety of anatomical structures and some of them should not be hurt. In a later stage, as an additional goal it should also be possible to understand how exactly the needle is controlled. This goal requires that the different elasticity of tissue types is conveyed, that is, haptics plays an essential role. With this addition, the SpineSurgeryTrainer partially belongs to a system for studying *operation techniques* [Kellermann *et al.*, 2011].

The refinement of the learning objectives as well as the discussion of the case database and the specific user interface were again focused on user stories, and derived conceptual and concrete scenarios (recall Benyon *et al.* [2005] and § 5.2.3.2). To convey this discussion, we cite portions of an essential concrete scenario [Cordes *et al.*, 2008]:

> *"During the planning of the injection the assistant doctor has to pay attention to follow the right injection path to avoid lesions of important structures and to place the needle to the target point [Comment 1]. To understand how to place the injection, he clicks on the help button in the menu and reads the help texts for this step. After that, he chooses the therapy by clicking the button "Injection" and starts the planning. With a left mouse click he defines one marker for the penetration point and one for the target point of the needle in the 2D view. Therefore, he has to navigate through the slices by using a slider next to the viewer. The needle takes up its position. In an animation (started by pressing the button "Show animation") the user can observe the injection of the needle to his defined position. He can also manually move the needle forwards and backwards, using a slider, to get a better impression of the injection path and the penetrated structures." [Comment 1: A warning should be presented, if a collision with important structures occurs.]*

The comment is just one example of feedback from experienced medical doctors. The learning objectives are not comprehensive, e.g., the insertion of an artificial spinal disk, the resection of a spinal disk or other related treatment steps cannot be trained.

Case Database The surgical intervention differs strongly depending on the specific vertebra involved. Thus, ideally the case database should contain cases from the cervical, thoracic, and lumbar spine. For each case, CT and MRI data are relevant and should be provided along with the segmentation information, e.g., the spinal canal. The image data, e.g., the selection of MR sequences is guided by the recognizability of the following structures:

- the vertebral bodies,
- the spinal disks,
- the dura, and
- the nerve roots.

As anatomical context also the thyroid gland, trachea, gullet, muscles and vessels should be delineated.

In addition to image data, again, a variety of other patient data is essential to support treatment decisions. These include age and weight, the history of pain, the results of a physical examination and the assessment of professional and leisure activities. The latter are also relevant to assess which limitations are crucial for the patient and need to be avoided. Again, revised (and anonymized) reports from surgery, videos, photographs, and expert descriptions related to the treatment decision and postoperative follow-up are provided.

In order to support decision-making, we deliberately integrated very similar cases where the "right" treatment decisions differ. To find such very similar cases in real patient data might be very difficult, since they might be rare. However, with enough medical knowledge, the data of one case may be slightly changed, e.g., by a small rotation of a prolapse or another minor shift in the anatomy to "create" the new case. Of course, care is necessary to avoid situations that are not plausible or even obviously impossible.

User Interface Design The concrete user interface design is guided by scenario-related specifications and a decomposition according to the components of the *four-component-instructional-design model* (recall van Merriënboer *et al.* [2002]). As an example, one subtask is to familiarize with 3D interaction (picking, zooming, rotation). This subtask is relevant for some trainees and is supported by a 3D viewer with a simple 3D model and step-by-step instruction. Any supportive information, e.g., help texts, are displayed along with a dialog or as balloon help.

Similar to the LiverSurgeryTrainer, a workflow is suggested and presented in the left column of the overall layout (see Fig. e21.24).

The user is directed through that workflow and offered information for each step. This information does not only relate to handling the system but also to expert comments describing and explaining their choices. In the *analysis step* the trainee can compare his or her therapy strategy visually and textually with those of two experts.

The visualization in this system is not optimized with respect to perceptual aspects. With an adaptive use of transparency, enhanced contrasts or an emphasis of the needle, the system's impression may certainly

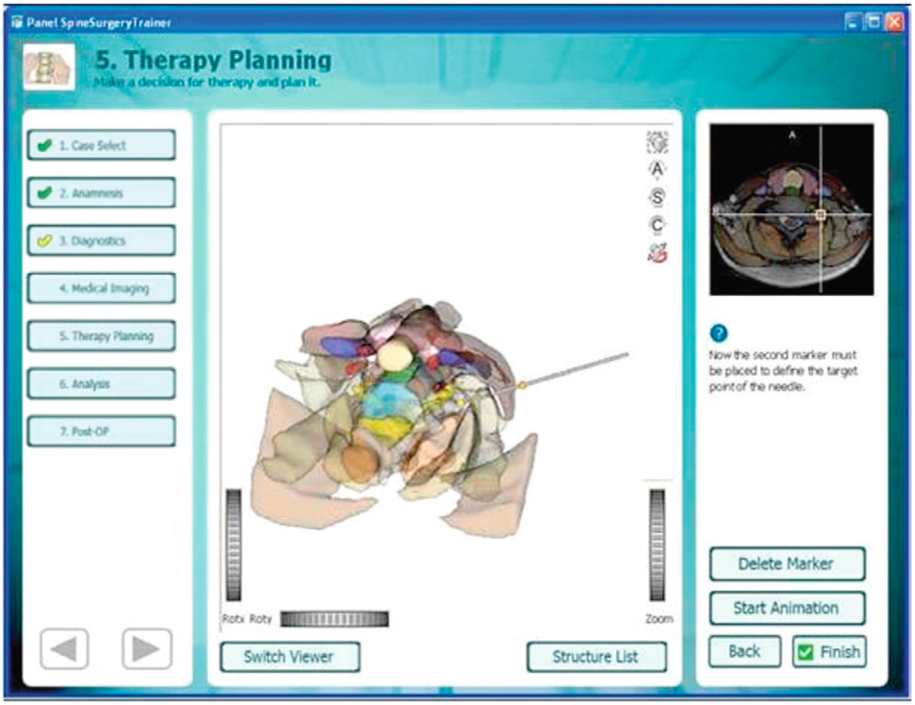

FIGURE e21.24 *Basic layout of the SpineSurgeryTrainer that follows the workflow represented by the steps in the left column. In the current step, the trainee can practice needle placement. The 3D model of the cervical spine region includes vertebrae, spinal disks, nerve roots, and surrounding structures. After defining the penetration and target point of the needle in a slice view, the trainee checks the position of the needle in the 3D model and observes an animation of the needle placement (Courtesy of Kathrin Hintz, University of Magdeburg).*

be improved. Needle insertion in a complex anatomical setting is also a use case where stereoscopic rendering is likely to be helpful.

The most essential task is to define the path of a needle. Since the needle is not elastic, it follows a linear path and thus the user has to define two distinct points:

- the *penetration point* (sometimes called *puncture point*), and
- the *target point* of the virtual needle.

2D and 3D visualizations are provided to define and eventually adjust these points. To convey the effects of a virtual needle insertion, the affected anatomical structures are emphasized. We also discussed to move them apart by virtual spread tools. An even better support would be achieved if a realistic soft tissue deformation would be integrated.

Evaluation An essential aspect in the informal evaluation was that trainees indeed understood *transitions* in the treatment decision due to small changes of the patient status. This is probably the most general finding of this development: Systems for training clinical surgery should be based on an analysis of such transitions and deliberately integrate them in the training process.

21.5 SIMULATION FOR SURGERY AND INTERVENTIONAL RADIOLOGY

Computer support for the study of operative techniques is motivated by the desire to avoid damage to patients early in the learning curve of a physician. The need for computer support in this area has strongly increased in the last years with the introduction of new endoscopic and other minimally-invasive interventions. In these procedures, endoscopic instruments and a camera are inserted into the patient's body through natural or artificial orifices. These procedures reduce the trauma for the patient and lead to faster recovery. For the surgeon, the direct view to the operating situs is missing and the surgeon has to learn the handling of new instruments developed for minimally-invasive use (see Fig. e21.25).

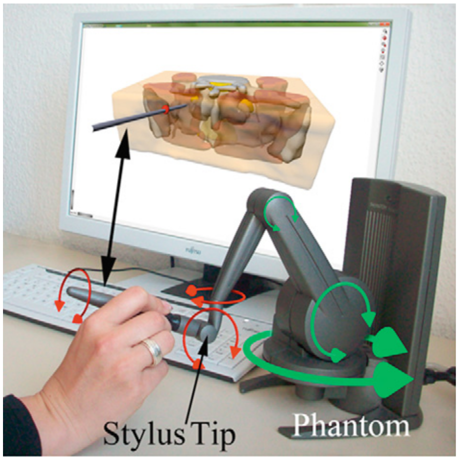

FIGURE e21.25 *In an extended version, needle placement is enhanced with force feedback. However, the tissue is still considered as static and thus, the realism of the training is limited (Courtesy of Kerstin Kellermann, University of Magdeburg).*

Even experienced surgeons have to obtain new skills, in particular with respect to the *eye-hand coordination*. It is documented for many interventions that the rate of complications is strongly related to the experience of the operator with this particular intervention. Therefore, a risk-free learning environment as well as the training of a wide range of clinical cases is required [Sierra *et al.*, 2003].

Without computer support, surgeons either use dedicated mechanical systems (referred to as "endo trainers" or "box trainers"), animals, or cadaveric material. The same elongated instruments as used in minimally-invasive interventions are used in these settings. Some mechanical systems are restricted to the manipulation of plastic objects which do not provide the elasticity of living tissue. The use of animals and cadaveric material is more realistic, but also not as realistic as desired—in particular the perfusion of living tissue makes a strong difference. Moreover, the use of animals poses ethical problems and is expensive. These drawbacks are the primary motivation for the development of surgery simulators [Delingette and Ayache, 2005].

Computer support for studying *operation techniques* requires surgery simulators that provide a look and feel close to real interventions at the living patient. Correct (visually realistic) organ models and textures are an important prerequisite. This requirement, however, also yields for anatomy education and relates to models and datasets (recall § 21.2.1).

The degree of realism that is actually required in training systems is an aspect of ongoing debate. The hypotheses that increased realism leads to faster or improved skills assessment have not really been supported by user studies. It is even discussed whether a certain amount of abstraction leads to optimal training effects in capabilities such as hand-eye coordination.

Oropesa *et al.* [2010] suggest that some of the distracting factors in a real operating situation should be avoided in virtual reality-based training. There is no definitive answer on how important an accurate visualization of bleedings, coagulation and fume actually is for the training effectiveness. However, for the acceptance of training among both trainees and experts, a high degree of realism is likely essential, even beyond the degree that improves efficiency.

Even the importance of force feedback for minimally-invasive training is questioned according to some study results. It may be sufficient to visually indicate closeness of an instrument to certain tissues. In the survey of Oropesa *et al.* [2010], three out of five surgical simulation systems provide force feedback only on an optional basis and one does not provide it at all. Figure e21.26 gives an example where the distance of a surgical instrument (trocar) to the spleen and pancreas is color-coded, instead of making use of force feedback.

A general decision in the design of surgical simulators is whether surface or volume representations should be used. Speed of rendering and collision detection are advantages of surface models [Brodlie *et al.*, 2000]. More accurate physical simulation is in general achieved with volume representations.

One essential aspect of realism in surgery simulators is the ability to perform arbitrary free-form cuts. This particular aspect was discussed in § 9.9, since it is also essential for surgery planning. However, we did not consider soft tissue deformation of the manipulated tissue that will be discussed in the following, along with other requirements essential for surgery simulation:

- *Soft tissue deformation*. Soft tissue should behave naturally when forces are applied and when the tissue is teared or cut.
- *Variable training scenarios*. Effective training requires variable scenarios with respect to anatomical variants, as well as to pathological variations, complications that need to be handled, etc.
- *Haptic interaction*. Realistic training with haptic devices is essential, in particular to support eye-hand coordination. Appropriate force-feedback devices are required and a fast update is necessary, since the tactile sense has a very high temporal resolution.

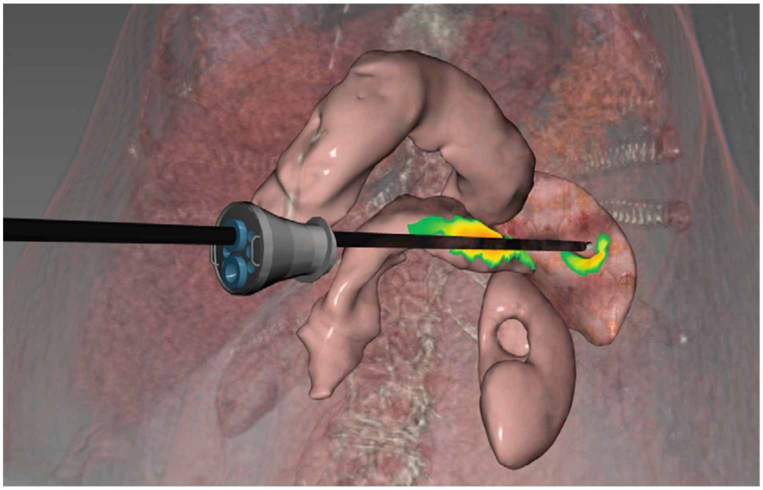

FIGURE e21.26 *When an instrument approaches an organ closer than a threshold, this distance is color-coded on the organ surface. The instrument is below the stomach and above the left kidney (Courtesy of Simon Adler, Fraunhofer IFF Magdeburg).*

- *Collision detection*. If surgical instruments touch anatomical structures (or other instruments), these collisions need to be detected very fast to initiate a physically plausible response.
- *Realization of surgical devices, procedures, and effects*. In surgical interventions, various devices, e.g., drill tools and scalpels, are employed in a well-defined manner. These devices need to be modeled with respect to geometry and behavior. The resulting effects, e.g., bleeding if vasculature is hurt, irrigation, and coagulation smoke, must be modeled in a plausible (not necessarily realistically) manner.

Figure e21.27 summarizes the components of a virtual reality surgical simulator, that we discuss in the following. In an implementation, the control flow may differ and may be more flexible than using a "central component" for all interactions between the components.

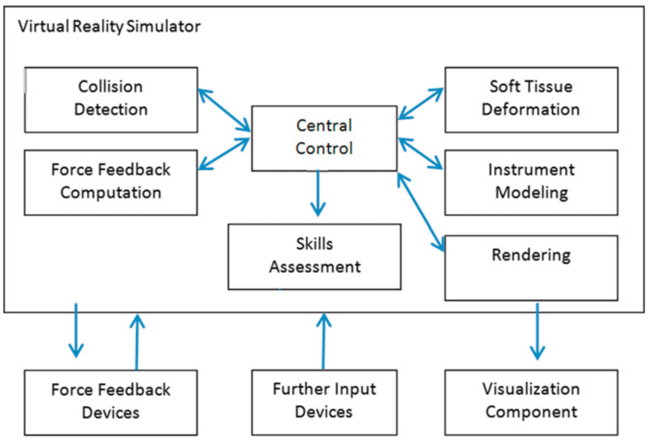

FIGURE e21.27 *Basic components of a virtual reality simulator and related input and output components as well as their interaction.*

Force feedback is realized with either one or two devices (*dual force feedback*), e.g., to practice needle placement while holding an ultrasound probe. The "visualization component" may be a conventional screen. However, to provide the desired level of immersion and engagement for procedural training, stereo rendering or even more immersive VR workbenches are useful (see, e.g., the work of Ullrich *et al.* [2010]). At least binocular goggles should be provided.

21.5.1 SOFT TISSUE DEFORMATION

Real-time and precise simulation of soft tissue deformation is still a major challenge. Different methods are used to accomplish the simulation, resulting in a different speed and accuracy. A realistic estimation of stiffness parameters (Young's modulus, shear modulus, bulk modulus, viscosity) is required as basis for the simulation models. The reliable approximation of these input parameters is difficult. Ex vivo measurements are not reliable, since the degree of perfusion of an organ has a strong influence on its elastic properties [Delingette and Ayache, 2005]. Non-invasive invivo measures may be accomplished by employing the fact that the elasticity of a sample is related to the velocity of sound waves which can be measured with ultrasound.

Soft tissue deformation in surgery simulators is in general based on the theory of continuum mechanics (more precisely *elasticity theory*) which has been used for a long time to analyze and predict deformations of elastic bodies. Human tissue is characterized by a non-linear relation between forces and resulting deformations. Also, hysteresis effects occur [Maurel *et al.*, 1998].

The method of reference to computationally handle elasticity theory is the Finite Element Method (FEM), which was briefly described in Chapter 19 in the context of CFD (computational fluid dynamics).

The specific resistance of tissue for a deformation is either derived directly from the image data or it is assigned to a specific tissue type. With CT data structures of high density, such as bones, have a high resistance, whereas structures with moderate or low intensity have a rather low resistance. More precise modeling is possible, if all relevant areas are segmented and assigned to a certain tissue type, such as skin, or muscle, and stiffness properties for these tissues are employed.

Finite Element Modeling Similar to blood flow, also the behavior of soft tissue can be described by the Navier-Stokes equations, systems of non-linear partial differential equations [Ciarlet, 1988]. FEM, based on an appropriate discretization of the spatial domain is employed to numerically approximate the solution of these equations. Similar to blood flow simulations, the discretization of the domain is often realized as a tetrahedral grid that is constructed based on a triangle surface mesh and completely fills the anatomical structure. As a difference, in soft tissue simulation it is usually not necessary to represent the wall-near structures with a higher accuracy (and different grid type).

Besides the grid type and the actual volume mesh, boundary conditions which restrict the deformation and the selection of appropriate time steps for the numerical solution influence the stability, the speed, and the accuracy of the solution. To prevent instabilities in the simulation, thin and elongated tetrahedra should be avoided. An overview on 3D mesh generation is given by Bern and Plassmann [1999].

FEM allows a precise modeling of soft tissue deformation. The deformations resulting from manipulations, such as poking, tearing, pulling, and cutting might be represented realistically. FEM has been used for surgery simulation for almost two decades (first described by Bro-Nielsen and Gramkow [1996]). In general, precise FEM simulations are very slow. This gave rise to a number of variations and completely different simulation methods.

For cutting, the affected tetrahedra need to be subdivided [Bielsen *et al.*, 1999]. This, however, may also introduce an increased stiffness of the system due to the increased element number. As an alternative, the nodes can be repositioned in order to prevent the complexity of the grid from increasing considerably [Nienhuys and van der Stappen, 2001]. A simplified version of FEM solutions (considering only linear elasticity) was presented by Nienhuys and van der Stappen [2001]. For small deformations (less than 10% of the organ size), *linear elasticity* is considered a valid approximation [Delingette and Ayache, 2005]. For a more recent overview on soft tissue deformation derived from continuum mechanics, see Famaey and VanderSloten [2008].

Simulation with Mass-spring Models Mass-spring models are based on a mesh consisting of masses (nodes) and springs which connect the masses (recall § 20.5.2, where we discussed the use of mass-spring models for model-based segmentation). Strut springs are often added to keep the mass-spring surfaces maintain their shape. Deformations are realized applying Hooke's law that performs a linear elasticity approximation (that is reasonable for small deformations).

The topology of the mesh and the spring parameters determine the behavior of a mass-spring model in a simulation. In order to simulate the dynamics of a mass-spring system, the relation between position, velocity, and acceleration for the mass m_i at point p_i at time t can be described as [Waters and Terzopoulos, 1990]:

$$F_i^{ext}(t) = m_i \frac{d^2 p_i(t)}{dt^2} + \gamma \frac{dp_i(t)}{dt} + F_i^{int}(t) \tag{e21.1}$$

γ denotes a damping factor, $F_i^{int}(t)$ denotes the internal elastic force caused by strains of adjacent springs of p_i. $F_i^{ext}(t)$ is the sum of all external forces. The dynamics is thus described by a system of second-order ordinary differential equations. For an efficient numerical solution, Equation e21.1 is typically reduced to two coupled first-order differential equations. Either Euler's method or a higher order Runge-Kutta method is employed to solve the equation system (recall [Waters and Terzopoulos, 1990]). Figure e21.28 illustrates the use of mass-spring models for simulating deformations and cutting procedures. Bro-Nielsen *et al.* [1998] used mass-spring models for an abdominal trauma surgery simulator.

To enable fast simulations, the propagation of forces in the mass-spring model may be restricted. Choi *et al.* [2003] suggest a layer model and estimate—depending on the depth of the penetration—which layers need to be considered in the force propagation. Obviously, based on the damping factors, more distant nodes in a mass-spring model are affected less. To avoid lengthy computations of small effects, the propagation may be stopped.

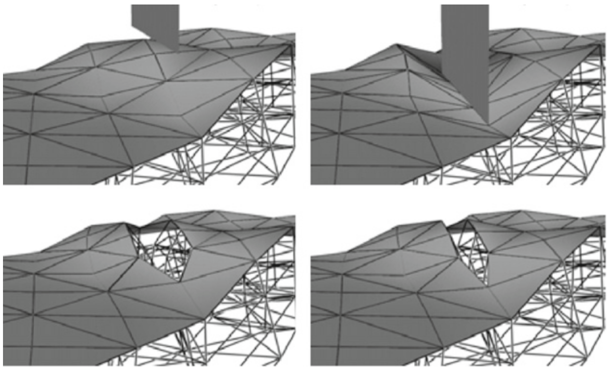

FIGURE e21.28 *Simulating soft tissue deformation with a surgical instrument using mass-spring models (images above). Also cutting procedures may be simulated in a plausible manner with mass-spring models (images below)* (From: [Teschner et al., 2000]).

Simulations based on mass-spring models are generally faster than simulations based on FEMs at the expense of accuracy. In general, it is difficult to derive spring constants such that a realistic behavior results.

21.5.2 VARIABLE TRAINING SCENARIOS

The need for variable training scenarios is described by Sierra *et al.* [2004]. They compare surgical training with flight training and argue that flight training with an invariable landscape and constant weather conditions would not be effective. Similar, repeated surgical training with the same organ "obscures training since the user adapts to this special anatomy." Three strategies are possible to develop variable training scenarios:

- A large number of individual patient data is selected and analyzed to represent the variety of anatomical and pathological variations.
- The data are generated with dedicated modeling tools instead of reconstructing models from clinical data.
- Based on a clinical datasets, *parameterizable models* of the anatomy and pathology are developed to generate individual cases flexibly. The problems of reconstructing, simplifying and smoothing surface models have to be solved within this strategy.

All three strategies have their merits and pitfalls. The first, more conventional strategy, requires to analyze a large variety of medical volume data, which involves laborious segmentation tasks. Even a larger selection might be considered as too restrictive by surgical users. The advantage of this method is that all examples are realistic with respect to the morphology of the relevant objects and the spatial relations between them. The second strategy requires an enormous modeling effort to provide sufficiently realistic models. Freeform modeling with variants of B-spline and Bézier patches is not only time-consuming, but requires considerable experience. An advantage of this strategy is that the problems of correcting and smoothing reconstructed models may be avoided.

The alternative is to employ either one or only a few models and adjust parameters to vary anatomical shapes and pathological variations. This strategy requires to study and represent the variability of anatomical structures as well as an understanding of the growth process of pathological variations. Care is necessary to avoid the generation of unrealistic models.

Parameterizable Models The use of parameterizable models for surgical training has been suggested by Sierra *et al.* [2004]. They use active shape models (ASM), often employed for model-based image segmentation (recall § 4.5.3 and Cootes *et al.* [1994]) to represent anatomical variations. By adjusting the major modes of variation, they can thus generate an arbitrary number of different instances of an organ. For pathological variations, statistical models are not feasible, since the range of pathological cases varies too strongly. Instead, they attempt to model the growth processes and came up with a model of tumor growth. Cellular automatons are based on a simple set of rules which allows to simulate a large variety of growing phenomena, including aspects of tumor growth. Such simulations should also consider that a pathology arises in a certain organ and is adapted to it and other surrounding structures [Sierra *et al.*, 2003].

Later, the tumor growth model was significantly enhanced [Lloyd *et al.*, 2007]. With the enhanced model, the growth of the tumor is coupled with angiogenic sprouting. Thus, the later stages of a tumor disease with significant neoangiogenesis are modeled and oxygen and blood support is integrated. Such a model is very useful for surgery simulation, but of course enables also more basic science experiments related to an *understanding* of tumor diseases.

Toward Automatic Mesh Generation The use of variable training scenarios also has consequences for other aspects of surgery simulation. It is no longer feasible to generate the meshes for soft tissue simulation with a large amount of manual work. Instead, the meshes have to be generated in a fully automatic fashion, which represents a serious difficulty, since the meshes have to fulfill a variety of requirements to allow an efficient and numerically stable simulation (recall § 19.3.2).

21.5.3 COLLISION DETECTION

Collision detection is the general term for algorithms that detect objects touching or penetrating each other. This information is essential, e.g., to provide realistic force feedback. But even without force feedback, collision detection provides increased realism. Otherwise, tools are just moved through bones and other anatomical structures leading to a very unrealistic experience.

Collision detection algorithms compute the

- pair of involved objects,
- the area of contact,
- the depth of a penetration, and
- the angle of penetration.

Training systems for surgery and interventional radiology require real-time feedback, which is difficult to achieve due to the typically large geometric complexity of anatomical structures. With this requirement, *penalty-based methods* are favored that apply a force that depends on the penetration depth of a rigid object in a deformable object [Raghupathi *et al.*, 2004].

There are different categories of collision detection problems and consequently different algorithms and data structures to perform the necessary computations fast and precise enough. In the training of surgery and interventional procedures, there are three fundamentally different situations:

- procedures applied to non-deformable objects, such as drilling a bone with a bone burr, and
- procedures, where soft tissue deformations occur, such as penetrating skin with a needle,
- procedures, where both the tool and the affected tissue are deformable objects, e.g., when a guide wire is inserted in a vascular structure.

Obviously, the second situation is more challenging than the first, since constant updates of a large geometry representation against which collisions are checked, is required. The third type of situation primarily occurs interventional radiology. It is even more demanding and viable solutions emerged only recently (and will be discussed later).

A comprehensive and up-to-date review of collision detection is given by Teschner *et al.* [2005]. In general, a discrimination is made between *rigid body* and *deformable object* collision detection. Self occlusions may occur when deformable objects are considered. Unfortunately, simulating soft tissue in surgery simulators falls into the latter class of collision detection problems. Volumetric as well as surface models are employed for surgical simulation and collision detection. With both kinds of models, a general strategy is to adapt the resolution of the surface or volume mesh by re-tessellating around the region of the cut.

Modeling of Surgical Tools Collision detection in surgical simulators usually considers surgical tools as non-deformable objects. The simplest (and fastest) representation of a surgical tool considers only *one* contact point at the tip of an instrument to be checked for collisions. For some instruments, e.g., a sphere-shaped burr for drilling bones, this would be a very coarse simplification (in § 21.7.2, we discuss the training of bone drilling).

In other systems, e.g., that presented by Basdogan *et al.* [2004], collision detection is applied to a straight line, greatly simplifying any device that is more complex than a needle. A cylinder representation is more accurate to reflect the volumetric nature of most tools.

Algorithms for collision detection fall into two categories:

- *deterministic algorithms*, which precisely compute collisions and related information, and
- *stochastic algorithms* that employ probabilistic assumptions and approximate the required information.

We do not consider stochastic algorithms here, although they are potentially useful for surgery simulation, since they allow to balance real-time requirements with accuracy. The interested reader is referred to Klein and Zachmann [2003].

Hierarchical Data Structures for Collision Detection To efficiently detect collisions, space partitioning schemes are employed (recall § 10.4 where such data structure for distance computations were discussed). Axis-aligned bounding boxes (AABB), oriented bounding boxes (OBB), k-dimensional discrete orientation polytops (k-DOPs), and bounding spheres are among the widely used data structures for efficient collision detection. With such data structures, the necessary tests and computations can be restricted to a subset of leafs of a hierarchy. However, the use of hierarchical data structures requires additional setup time to construct the hierarchy and additional time to update and adapt the hierarchy as a consequence of motions and collisions.

For the non-rigid soft tissue objects considered in surgery simulation, the update process is considerably more complex than for rigid objects. Teschner *et al.* [2005] argue that for this task AABBs are the most appropriate data structure. Here, the structure of an AABB tree can be kept, but the extent of the nodes has to be corrected. Other structures, e.g., k-DOPs and OBBs, enclose the geometry more tightly (see also vanDenBergen [1997]). Spillmann *et al.* [2007] employed bounding spheres hierarchies and combined collision detection with an efficient *collision response*, using the again the hierarchy for efficiency.

An efficient collision handling scheme was introduced by García-Pérez *et al.* [2009]. They applied a fuzzy logic scheme to infer parameters of the collision response. With this system, the interpenetration of several vertices, affected by a collision, may be avoided. The system aims particularly at laparoscopic surgery simulators.

Collision Detection for Simulating Intravascular Interventions While general solutions for efficient collision detections are available and mature, there is still a demand for refined and advanced algorithms to cope with special challenges. As an example, the collisions of instruments moved inside vascular structures with the vessel wall, are very expensive to compute with the methods described above. This is due to the fact that the instruments are so close to the complex vascular anatomy that the computation does not benefit strongly from the object hierarchy. Li *et al.* [2012] present a solution to reduce the search space for collisions using a search tree that represents the vessel centerline and its bifurcations. Such support is indeed necessary to achieve real-time performance in training systems for intravascular interventions (see § 21.6.5).

21.5.4 FORCE AND TACTILE FEEDBACK

We briefly discussed force feedback in § 5.7.2. Due to its particular importance for training interventional radiology and surgery we extend this discussion here.

The tactile sense plays an essential role for any task where objects should be grasped in virtual reality. Movement times are reduced and the perceived level of difficulty decreases simultaneously. These aspects are in particular relevant in many surgical tasks. Force feedback adds to the effect of collision detection—both features improve the exploration of a complex target anatomy and make it faster [Kellermann *et al.*, 2011]. Three main categories of haptics are essential for surgery and interventional procedures [Coles *et al.*, 2011]:

- *tactile feedback*,
- *force feedback*, and
- *torque feedback*.

Tactile Feedback represents our sensations when deliberately touching a surface. Tactile includes a sensation of the roughness, stiffness, and texture, as well as the sensation of wetness and temperature. In medicine it is essential for palpation, e.g., palpation of the pulse, or a surface-near tumor.

Force Feedback represents the resistance of obstacle. Thus, force feedback is crucial for needle placement tasks where the resistance of different tissue types when being penetrated needs to be perceived. Blunt dissection is another important surgical task where force feedback leads to lower error rates and reduced task completion times [Wagner *et al.*, 2002].

Torque Feedback is perceived when an instrument is rotated. It is closely related to force feedback, since it also represents a sense of resistance. Catheters and guide wires are strongly sensitive for torque movements, since almost no twisting occurs.

All these components of haptic feedback are based on computing forces representing the interaction between surgical devices or other instruments and the patient's anatomy. Ideally, all three components are computed. Force feedback depends on the position and orientation of the applied force, i.e., an accurate force feedback needs to be computed for six degrees of freedom (DOF).

This computation must be very efficient, since a high update rate is necessary to be perceived as realistic. The magic number, cited very often, is that a frequency of 1 kHZ is the minimum. Coles *et al.* [2011] discuss a number of precise investigations that indicate that the necessary frequency is overestimated with 1 kHz. The credible study performed by Booth *et al.* [2003] leads to a minimum frequency of 550–600 Hz and considers that this number also depends on the specific kind of contact. Stiff contacts require a slightly higher frequency of feedback than softer contacts. In essence, the necessary update rate is significantly higher than that for visual feedback (30 Hz), which gives rise to different geometric representations. Thus, while rendering is performed with an accurate geometric representation, the necessary computations for providing force and tactile feedback are performed based on representations with a lower resolution.

21.5.4.1 Force Feedback and Tactile Devices

Force Feedback Devices were announced in the 1960s by the computer graphics pioneer Ivan Sutherland and realized for the first time in the famous project Grope a decade later [Batter and Brooks, 1971].

Meanwhile, there is a variety of tactile input devices available. Due to high demands on accuracy low cost devices primarily developed for computer games are currently not appropriate for surgery simulation. However, these devices are in fast development and it may be possible that similar to the effect of GPUs for visualization also in haptics rendering, devices from the game industry get broadly accepted. Tactile input devices provide a *grasp*, e.g., a stylus. Two different kind of grasps are *precision grasps* and *power grasps*, suitable for different applications.

Most surgery simulators are based on the PHANTOM devices from SensAble Technologies. There are devices providing three degrees of freedom (3-DOF) representing translations in the *x*-, *y*-, and *z*-direction (PHANTOM Omni) and advanced devices providing 6-DOF haptics (PHANTOM Premium). These advanced and more expensive devices allow to transform objects in three translational and three rotational directions. 3-DOF devices are adequate to represent point-based interactions between surgical devices and the anatomy (the surgical device or more general the manipulator is represented as a point). If more advanced interactions, such as line-surface interactions, should be represented, 6-DOF devices are required. The PHANTOM devices exhibit a pen-based end-effector, often called a *stylus*.

In general, there are three categories of haptic input devices:

- *general haptic devices*, e.g., joysticks developed for the gaming market,
- *modified haptic devices* that resemble the actual instruments, e.g., syringe and needle, and
- *dedicated haptic devices* for training surgery and intervention.

The obvious advantage of general devices is that they are widespread, carefully tested and rather cheap. They often have end effectors that are shaped as pens or balls [Coles *et al.*, 2011]. The second option is often a good trade-off, since it avoids most of the challenges of developing a completely new device. Primarily, the grips are modified to provide a greater degree of realism (see Fig. e21.29 for an example). Among the widely available devices, only those that provide 6-DOF force feedback and torque feedback are able to simulate the full spectrum of movements in interventions.

Tactile Devices While force feedback is rather simple and well understood, tactile feedback depends on many aspects involving various receptors. Coles *et al.* [2011] mention 13 different technologies and devices based on this variety. Most of them are heavy, non-portable solutions. While tactile devices play a role in master-slave robots, such as the DAVINCI system, they currently have a very limited role in training

FIGURE e21.29 *A Sensable Phantom Omni device modified to mount the actual needle used during a procedure (Courtesy of Nigel John, Bangor University).*

systems. One aspect, however is that, the *vibrotactile sensation* is easier to simulate and may be used for medical education systems. Many users are aware of vibrations produced by a mobile phone that is silent to alert the user when a message or call comes in. Vibration does not provide the rich high-dimensional information of sensing a surface but it may provide useful feedback, e.g., when a bone burr is simulated, since the real process is also characterized by substantial vibrations.

21.5.4.2 Haptic Rendering

Haptic rendering is the process of calculating a reaction force (the *collision response*) for a specified position of the haptic input device. Usually, this position is represented as a point indicating the endpoint of the haptic device [Laycock and Day, 2003]. Haptic rendering becomes more complex (and more realistic) when the computation is not restricted to a single point representing the tip of an instrument.

The first step of a haptic rendering algorithm is collision detection discussed above. For haptic rendering, the instruments and tools are usually reduced to a few representative points. The second step involves the determination of the intersected area of the manipulated object and the determination of the penetration depth. Based on this information, a force is computed and applied to the arm of the tactile input device.

Efficient Solutions Based on Multimodal Representations Due to the high performance requirements of collision detection and haptic rendering, often models of different type and spatial resolution are employed for visualization, soft tissue deformation and collision detection/force feedback (*multimodal representation*). The highest resolution is employed for the visualization model and this model needs to represent the surface only. For soft tissue deformation a tetrahedral mesh of moderate resolution is a typical choice. Collision detection, as mentioned above, benefits from hierarchical data structures, such as a bounding sphere hierarchy (see Fig. e21.30). Of course, these representations have to be synchronized with each other: When the liver tissue moves, both the visual representation and the collision detection representation have to be adapted accordingly.

Software Support To actually provide an application with tactile feedback not only requires an appropriate input device, but also software to control the device. Research work in surgery simulation is typically based on one of the following solutions:

- the GHOST library that is provided by SensAble Technologies to control the PHANTOM devices,
- the OPEN HAPTICS toolkit also provided by SensAble,
- the REACHIN API,

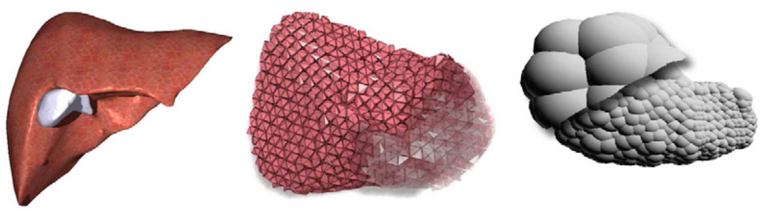

FIGURE e21.30 ***Left:*** *The visualization (of liver and gall bladder) is based on a high resolution triangle mesh representing the surface only.* ***Middle:*** *The tetrahedra representation is appropriate for soft tissue deformation.* ***Right:*** *The bounding sphere hierarchy is used for fast collision detection (Courtesy of Simon Adler, Fraunhofer IFF Magdeburg).*

- the HaptX engine, developed for gaming
- the open source Chai3D software,[11] as well as
- systems based on hardware from Immersion Medical, Xitact, and Force Dimension.

The ReachIn API as well as HaptX are provided by ReachIn. Open Haptics, although being commercial, is free for academic use [Coles *et al.*, 2011]. Chai3D is a rather comprehensive system with many examples and careful documentation supporting various platforms. However, at the time of writing, the latest available version is more than three years old. Thus, the development may have a low level of activity. Coles *et al.* [2011] describe these (and a few more) systems in more detail.

Discussion Haptic rendering is still not as mature as visual display technology. In particular tactile feedback is very difficult to provide accurately, since the biological processes that occur are only partially understood [Coles *et al.*, 2011]. Due to the significant computational effort and the necessary high update rate, most haptic rendering systems are still restricted. As discussed for collision detection, surgical instruments are usually considered as rigid-body objects. However, there are surgical interventions where the flexibility of the tool is crucial. As example serves root canal surgery in dentistry. A first prototype for the simulation of deformable tools is presented in [Laycock and Day, 2003].

Moreover, soft tissue deformation and haptic rendering is usually restricted to a single organ. In reality, deformations of one organ affect neighboring organs and the deformation of one organ depends on the neighboring organs.

Most systems provide force feedback only for anatomical structures that have been segmented and assigned properties, such as the Young modulus and stiffness. This restriction can be overcome with *haptic volume rendering* [Lundin *et al.*, 2005]. Haptic volume rendering resembles gray level gradient shading [Höhne and Bernstein, 1986]. Instead of using surface normals for shading, local intensity differences are analyzed and a gradient direction is determined on the voxel level. The image intensity, in case of CT data the Hounsfield value, is also considered to influence the amount of force feedback. The haptic forces differ along the needle.

21.5.5 SOFTWARE FOR SURGERY SIMULATION

The simulation of interventional procedures and surgery made substantial progress in recent years also because of the availability of powerful toolkits. We briefly describe three widespread frameworks in chronological order of introduction.

Spring The Spring framework includes soft tissue simulation, cutting, haptics and collision detection [Montgomery *et al.*, 2002]. It was extended by the authors of the toolkit to incorporate various special effects that are essential for realistic surgery simulation. At the time of writing, the website is no longer available.

GiPSi The GiPSi framework (General interactive Physical Simulation interface)[12] provides comprehensive support for the simulation, including linear and non-linear FEM based on solvers for differential equations. Different models for visualization and simulation are supported, including their synchronization [Cavusoglu *et al.*, 2006, Goktekin *et al.*, 2004]. The showcase example motivating the development was heart simulation. Haptic device handling and collision detection are not supported.

11 http://www.chai3d.org.
12 http://gipsi.case.edu/.

SOFA Finally, the SOFA framework (Simulation Open Framework Architecture)[13] should be mentioned. It is the most comprehensive framework based on a large development team.

It provides three distinct models: a collision model, a visual model and a behavioral model (for soft tissue deformation) and thus support efficient multimodal representations as shown in Figure e21.30. These models differ in resolution and thus are separated. Different tasks operating on these are also performed in different threads. Synchronization is also supported. Powerful solvers for differential equations and linear equation systems are provided. Parameters of the simulation, e.g., collision algorithms, constraints, and solvers, are described in XML files, which enables simple editing. Complex models may be created with a scene graph description. The whole design targets at optimal reuse.

SOFA was introduced by Allard *et al.* [2007] and became widespread after a series of presentations at MICCAI, SIGGRAPH, and VCBM in 2010. A number of additional features were integrated meanwhile and further investigations were performed. Marchal *et al.* [2008] discuss the validation and verification of the soft tissue deformation provided by SOFA, including the numerical approximation and the assessment of the realism of the physical behavior. They emphasize that open source software, such as SoFa enables a comparison of algorithms and metrics. Saupin *et al.* [2008] described precise methods for contact modeling to improve haptic realism in surgical simulators. Various simulation techniques, including mass-spring and FE models.

SOFA is available on the Linux, MacOS, and Windows platforms. The comprehensive system consisted of 450,000 lines of code in October 2012.

Both GiPSi and SOFA are active developments at the time of writing.

21.6 SIMULATION FOR TRAINING INTERVENTIONAL PROCEDURES

The training of interventions and the training of surgery have many common aspects but also distinctive features that warrant to treat them in separate sections. Interventions are performed by interventional (neuro)radiologists or cardiologists under control of imaging and thus have different target audience than surgery training systems. While open surgery usually does not require frequent intraoperative imaging (with some exceptions, e.g., in neurosurgery), minimally-invasive procedures raise similar challenges like interventions, namely a difficult hand-eye coordination and tissue handling. In contrast to interventions, live full-color high resolution images from a camera are displayed in minimally-invasive surgery instead of a rather low-resolution gray scale image, e.g., from fluoroscopy. Among the similarities is the general approach for computer-assisted training that involves a pretest, the actual training stage and a posttest for skills assessment. Tissue handling is also a common problem. In open surgery, special skills, such as accurately drilling bones, are essential.

21.6.1 NEEDLE-BASED INTERVENTIONS

Before we describe specific examples, we discuss some general aspects of needle-based interventions. Needle-based interventions are frequently applied, e.g., to obtain tissue samples (*biopsy*), to inject fluids, e.g., in regional anesthesia, or as a prerequisite for more advanced procedures, e.g., in vascular interventions. Before needles are actually inserted, the presence of anatomical features is verified, primarily by palpation, thus involving subtle tactile sensations [Coles and John, 2010]. While biopsy needles may be considered to be straight linear rods, guide wires and catheters used to treat vascular diseases are flexible

13 http://www.sofa-framework.org/.

and adapt to some extent to the surrounding anatomy. Needles may penetrate skin and soft tissue, but are not able to penetrate skeletal structures. Haptic forces that are simulated for training needle placement must consider at least two different components:

- *friction* that occurs when the needle is moved tangential to a surface, and
- *penetration* when the needle is moved in the orthogonal direction and thus enters a structure.

Of course, the gliding movement that causes friction requires considerably lower forces than the penetration. Moreover, in a penetration situation, suddenly the necessary force drops significantly. In general, needles deform anatomical surfaces only locally. Thus, the computation of deformation forces should be restricted to a small region around the needle tip in order to provide a fast response. However, even these local changes may require to remesh the surface models because at least some tetrahedra may degenerate.

Currently, most needle insertion training systems are trained with modified force feedback devices (recall Fig. e21.29).

21.6.2 HAPTIC DEVICES FOR NEEDLE-BASED INTERVENTIONS

Physicians need to carefully control the orientation of needles, their depth by advancing or pulling the needle. In § 21.5.4, we introduced general, modified, and dedicate haptic input devices.

Although 6-DOF devices are desirable, also systems using haptic devices with 3-DOF were employed, to provide cheap solutions. An example is the CathSim Accu-Touch system.

To acquire the necessary motor skills for needle-based interventions, a special haptic device is highly beneficial. Luboz *et al.* [2009] introduce such a device based on the optical sensors of a 2D mouse. The shell of the mouse was removed to provide access to the roller ball. A 3 mm hole was drilled in the roller ball to accommodate a catheter. The depth is measured with a potentiometer with this design, the needle may be rotated by around 45° which is sufficient for simulating needle punctures. The optical sensors of a mouse, however, are not very accurate: They enable an angular resolution of 3°, which is sufficient for determining whether the vessel was indeed punctured, but an improved accuracy was considered desirable [Luboz *et al.*, 2009]. For an in-depth discussion of haptic devices and their suitability for training needle-based interventions, see Coles *et al.* [2011]. They compare the Falcon device from Novint, the devices produced by SensAble technologies and those by Force Dimensions. In the comparison,

- the price,
- the degrees of freedom for force feedback,
- the supported workspace,
- the availability of torque feedback as well as
- the frequency of use in interventional training

are considered.

21.6.3 SIMULATION OF LUMBAR PUNCTURES

We have already introduced the medical background of lumbar punctures in § 21.4.3. In this diagnostic procedure a biopsy needle is moved in the spinal canal to extract cerebrospinal fluid. The procedure is easier in case of slim patients and more difficult in case of obese patients. Lumbar punctures can be trained with dolls to some extent, but the complex anatomy cannot be understood from such training [Färber *et al.*, 2009]. A more realistic training involves soft tissue deformation and force feedback and preferably involves cases that differ in their degree of difficulty.

Early attempts at such simulators, e.g., [Singh *et al.*, 1994], provide force feedback only in three dimensions. That means that only the needle position may be transformed but not the needle orientation. More recent systems, e.g., the training system presented by Färber *et al.* [2009], Kellermann *et al.* [2011] provide 6-DOF force feedback. The virtual penetration of the skin with force feedback benefits from modeling friction. A moderate friction value (0.5 in a 0–1 range) supports in gliding along the skin and was reported to be more efficient than free-hand control [Kellermann *et al.*, 2011].

To support learning, it is sometimes better to deviate from realistic behavior. The discussions with surgeons, underlying the design of the SpineSurgeryTrainer, revealed that they want to touch and clearly feel vulnerable structures, such as nerves and vascular structures. Thus, in contrast to their real-world behavior, they were assigned high stiffness values in order to support this tactile experience [Kellermann *et al.*, 2011]. To support early stages of learning, even the needle insertion was performed differently than in reality. Users first chose a target point and then determined the orientation, whereas in reality, of course, a needle first has to penetrate the skin (Fig. e21.31).

Färber *et al.* [2009] suggest to compute the forces for the needle tip as well as for 15 positions along the needle. The trainee uses a setup with a virtual reality workbench and stereo glasses to have an immersive experiences (see Fig. e21.32). 2D and 3D visualizations are provided to fully understand the needle position and orientation in the anatomical context.

In the following, we describe some more aspects of lumbar puncture training system developed at the University of Lübeck in a long-term project [Färber *et al.*, 2009, Fortmeier *et al.*, 2012, 2013a]

Case Database and Didactic Concept The training system employs the Visible Human and Visible Korean datasets making available also the colored slice visualizations. In addition, three patient data datasets, representing different degrees of difficulty, are employed. The system can be operated in three different modes aiming at beginners, advanced users, and experts. The visualization options and guidance by the system are adjusted according to this selection. Figure e21.33 illustrates the visualization options.

Evaluation The evaluation of the system was based on a questionnaire representing the assessment of the trainees and based on objective data gathered during the training session. Prior to the actual test, trainees were made familiar with force feedback using a very simple and artificial scene. In the questionnaire, a number of statements were made and the trainees commented how strongly they agree or disagree (a six point Likert scale with 1 representing strong agreement and 6 strong disagreement). With 42 users, the results are rather stable.

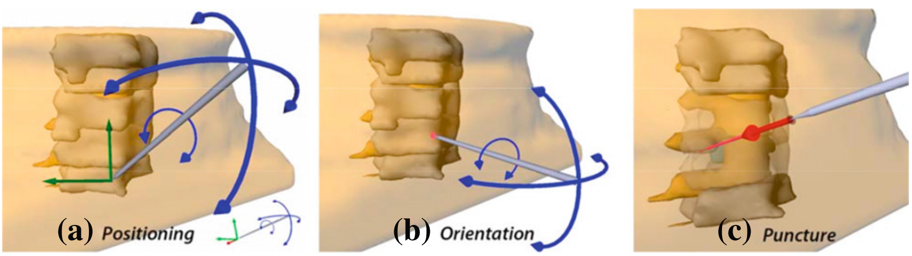

FIGURE e21.31 *Training workflow in the enhanced* SpineSurgeryTrainer. ***Left:*** *The target point in the spine region is defined first and then the needle tip is locked.* ***Middle:*** *After gliding along the skin, orientation of the biopsy needle is determined.* ***Right:*** *The needle is advanced until the right penetration depth is achieved (Courtesy of Kerstin Kellermann, University of Magdeburg).*

FIGURE e21.32 *Setup of the system for training lumbar punctures with a tactile input device and a VR workbench (Courtesy of Mathias Färber, University of Lübeck).*

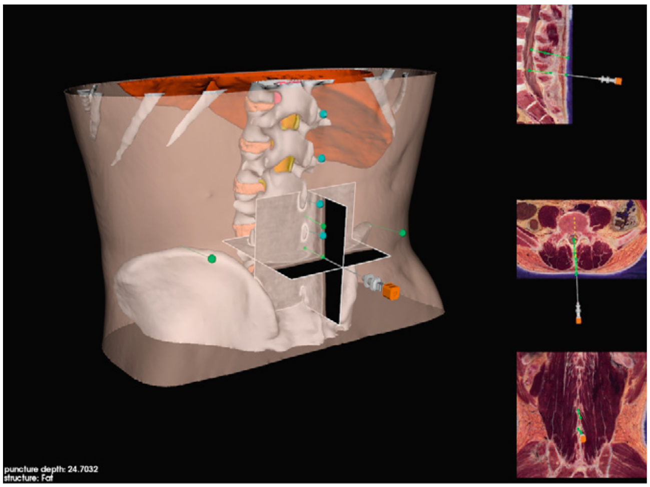

FIGURE e21.33 *Needle insertion based on the Visible Human dataset (see colored slice views on the right). A 3D overview visualization and a close-up primarily provide visual feedback (Courtesy of Mathias Färber, University of Lübeck).*

Users clearly felt different tissue as a consequence of haptic feedback (average 1.5). They also assessed the different visualization options as helpful for understanding the spine anatomy (1.6) and thus considered the overall training as useful (1.5). The display of patients was regarded as realistic, although with lower agreement (2.0). From the literature on human computer interaction it is known that test persons tend to be more positive than the general population outside of a test, in particular if they cannot compare alternatives. Thus, the absolute numbers need to be interpreted with care. However, the differences, e.g., between the usefulness of stereoscopic viewing and force feedback likely transfer to the larger target group.

On the objective side it was assessed whether the trainees successfully completed needle insertion, that is, whether they actually reached the spinal canal. Based on various components, an overall score representing the efficiency of treatment was registered. A particularly interesting detail is how strongly the results differed between two cases: A dataset of an obese patient and the Visible Korean dataset. Test persons have a much higher success rate and score with the Visible Korean dataset.

21.6.4 ULTRASOUND-GUIDED BIOPSY SIMULATION

To remove tissue samples based on ultrasound guidance is a frequent task in clinical routine, e.g., in the abdominal region. It is also a prerequisite for other interventional procedures, such as draining bile from the liver. An ultrasound probe is moved to the target region and provides a life image of the target anatomy. Biopsies need to be performed with care, since even thin biopsy needles may cause bleedings. To actually localize the pathology may be difficult, in particular, if it is small, hard to discriminate from surrounding tissue, deep-seated or difficult to access due to adjacent structures at risks or impenetrable bones. Training systems should incorporate such challenging situations.

Ni and colleagues developed a system that supports this navigation task [Ni *et al.*, 2008, 2011]. It is based on ultrasound data that was acquired at different time steps and later composed to a panoramic view (note that the field of view of ultrasound is limited). This composition is difficult for ultrasound data with its inherent artifacts but could be solved sufficiently. Very accurate force profiles for the relevant tissue types, e.g., muscles and skin are incorporated to provide the necessary haptic realism. They are based on earlier work by Brett *et al.* [1997b]. Force and torque feedback is provided. An enhanced degree of realism was achieved by Vidal *et al.* [2008], where the grip of the force feedback device was modified to resemble an ultrasound probe. In this system, a second force feedback device was used to simulate the needle.

Respiratory Motion An essential problem for biopsies in the abdominal region is the respiratory motion that complicates the localization of small targets. Thus, it needs to be incorporated in a realistic training system as well. Respiratory motion can be very different with respect to the extent of motion and temporal patterns. For training, a rather simple periodic pattern is probably sufficient. An elliptical area of influence was modeled as a reasonable tradeoff between accuracy and performance.

21.6.5 SIMULATION OF CATHETERS AND GUIDE WIRE INSERTION

Increasingly more pathologies are treated by means of catheters inserted to a vascular structure, e.g., to re-open a strongly calcified vessel. Such *endovascular* procedures are performed to treat cerebral vasculature, e.g., in case of a stroke, coronary vasculature, e.g., in case of coronary artery diseases, or peripheral vasculature.

21.6.5.1 Medical Background

Catheters and guide wires are inserted in the vasculature to treat these diseases with a minimum of patient discomfort compared to open vascular surgery. Angioplasty, stenting and coil embolization are examples for intravascular interventions.

FIGURE e21.34 **Left:** *A flexible catheter with control unit.* **Right:** *A balloon catheter that expands to treat stenosis (Courtesy of Axel Böse, University of Magdeburg).*

Catheters are thin long, often flexible tools and their shape and material is refined for special interventional procedures. Figure e21.34 displays two catheters that may be employed for treating vascular diseases. The insertion of a catheter is referred to as *catheterization*.

Guide wires and catheters may be very long: 1 or even 1.7 m are possible which needs to be reflected in the training. When the guide wire is in a sufficiently advanced position, the puncture needle is removed and the guide wire is used as a conduit for the catheter. The combination of guide wire and catheter is translated (pushed and pulled) and rotated by the physician, using the grasp at the proximal end for steering.

Not all vascular diseases can actually be treated in this minimally-invasive manner. In particular, when sufficient access is required for open vascular surgery, e.g., bypass surgery is still necessary. In the case of an interventional procedure, the "right" catheter needs to be selected, e.g., with respect to length, thickness, shape, and elasticity. Although decision support for the choice of treatment is also desirable, we focus on training systems to actually perform the intravascular procedure. Readers interested in the medical procedures are referred to Schneider [2003].

21.6.5.2 Vascular Modeling

An essential prerequisite for the simulation is an appropriate surface mesh representing the relevant part of a vascular system.

Requirements The vascular surface mesh representation should be smooth and accurate and should not contain any internal structures that would hamper the movement of a catheter. These requirements are the same as those for virtual angioscopy an endoscopic procedure to move a camera through vasculature (recall § 13.6.3).

Moreover, it should be appropriate for a fast and numerically stable simulation, that is, the triangle quality needs to be high (degenerated triangles with very small angles need to be avoided) and the geometric complexity should be low. These additional requirements are very similar to those of blood flow simulation where the surface mesh also serves as input for volume mesh generation (§ 19.3.2).

Selection of a Modeling Technique In Chapter 11, we introduced a number of vascular surface modeling techniques. Here, we discuss which of them fulfills the set of requirements stated above. Even the best explicit surface reconstruction, e.g., based on truncated cones, cannot avoid internal polygons and exhibits discontinuities at branchings [Hahn *et al.*, 2001].

Convolution surfaces [Oeltze and Preim, 2005] avoid these problems but require a remeshing step to ensure a sufficient triangle quality. Other implicit surface representations are more accurate and exhibit a better triangle quality, e.g., the modified MPU implicits (recall § 11.6.2 and Schumann *et al.* [2008], Wu *et al.* [2010]). However, even better quality is possible with more recent surface modeling techniques, which perform polygonization in an adaptive manner, creating a high resolution only in highly curved areas [Kretschmar *et al.*, 2012]. Similarly good results may be achieved with subdivision surfaces.

One method that we briefly introduced in Chapter 11 is based on *sweeping* and implicitly reconstructs vascular models [Li and Tian, 2009]. This method has been explicitly refined for using it in catheterization training [Li *et al.*, 2012]. They put emphasis on correctly representing branches and compose a vascular tree of tubular segments and a branching model that are smoothly blended. Bezier surfaces and sweeping are the basic methods and ensure that the surface normal changes continuously.

21.6.5.3 Catheter and Guide Wire Modeling

A training system for learning intravascular procedures requires to simulate the elastic behavior of the associated instruments, in particular of *guide wires* and *catheters*.

Physical Effects Catheters and guide wires are elastic and inextensible. There are various further effects to be considered, e.g., the guide wire is influenced by friction against the vessel wall. The catheter is restricted by the vessel wall (unless excessive power against it is applied). The catheter tends toward a state of minimum potential energy after the input of the physician stops. The potential energy E equals the sum of its bending, twisting and stretching energy (the three terms in Eq. e21.2) [Huang *et al.*, 2011].

$$E = 1/2 \int \mu\kappa^2 ds + 1/2 \int \beta m^2 ds + 1/2 \sum_{0}^{n-1} k(\overline{e}_j - e_j)^2 \tag{e21.2}$$

In this equation, s represents the arc-length parameterized centerline, μ the stiffness tensor, k the 2D curvature vector along the centerline, m the material twist, $\overline{e}_j$ and e_j represent the initial and current edge length.

An essential property of most guide wires and catheters is that they are highly resistant against twist. Thus, the physician has excellent torque control and some authors, e.g., Li *et al.* [2012] neglect the twist in modeling the dynamics. Since these devices are inextensible, a length-constraint should be included in the simulation [Huang *et al.*, 2011]. The flexibility of the tip of the catheter differs strongly from the remaining part. Thus, this property is relevant and incorporated in recent training simulators [Tang *et al.*, 2012]. Guide wires and catheters are modeled as sets of (straight) linear rods.

The deformation of the vessel wall and the deformation of guide wires and catheters are two tightly connected processes and need to be simulated as a coupled process to achieve a high degree of realism.

Modeling Technology Since catheters and guide wires are very long structures, they are in most systems modeled as 1D objects. Thus, the whole volume is adapted as a consequence of moving node positions arranged at a 1D chain.

The material parameters of guide wires and catheters are known. Thus, finite element modeling enables to accurately simulate the effects. However, the underlying effects are non-linear, leading to a very high computational effort when typical solvers, such as Lagrangian multipliers [Li *et al.*, 2012, Spillmann and Harders, 2010], are employed. Fortunately, the necessary computations can also be performed efficiently on the GPU [Taylor *et al.*, 2008].

An advanced system for guide wire simulation was developed at the Image Sciences Institute in Rotterdam [Alderliesten *et al.*, 2007]. It employs *Cosserat models* for a higher-order finite element simulation. Cosserat models are based on the elasticity theory provided by the French mathematician EUGÈNE COSSERAT. According to this theory, a local rotation of points as well as the translation is considered. In addition to classic elasticity, which only considers one kind of stress, both a couple stress (a torque per unit area) and a force stress (force per unit area) are modeled. Cosserat models were heavily used in biomechanics, e.g., to predict the response of bone to forces [Park and Lakes, 1986]. They have also been used in surgical simulation, see for example Spillmann and Teschner [2009]. With the Cosserat model, a guide wire is composed of a set of straight non-bendable beams. This model enables very good torque control [Luboz *et al.*, 2009]. The models consider two types of energy:

- bending energy, and
- external contact.

This non-linear modeling scheme enables accurate, however time-consuming solutions. While the system introduced by Alderliesten *et al.* [2007] could not achieve real-time behavior, more recent catheterization training systems accelerated the computation to enable real-time behavior [Tang *et al.*, 2012].

Catheters may also be simulated with mass-spring models. An early system was described by Basdogan *et al.* [2001]. Masses were defined as particles distributed around the centerline of the catheter. The careful definition of damping elements and torsion control enables reasonably realistic results with less computational effort. Luboz *et al.* [2009] present a comprehensive and advanced system based on a complete environment including a haptic device—developed for interventional radiology. The simulator contains a *pulse simulator* to train the location of the femoral artery of a patient model.

To provide the necessary performance, the simulator for training the Seldinger technique [Luboz *et al.*, 2009] is realized as a mass-spring model with appropriate distribution of particles (representing masses). Up to 700 particles are employed, resulting in a resolution of 2 mm for a 1.4 m catheter (from the femoral arteries to the neck vessels). The different structures may collide with each other—in these cases the needle has top priority, that is, other instruments strictly follow the needle.

Multigrid Solvers Without presenting any detail, we want to mention the recently introduced iterative multigrid strategy for catheter simulation [Li *et al.*, 2012]. The final solution is achieved by performing several steps of the simulation using a hierarchy of representations—a strategy that is useful for a variety of medical image computing problems, e.g., for registration. For the sake of brevity, we cannot discuss the validation of these and related procedures: the basic idea is to use physical phantoms and to compare the behavior of real catheters with virtual catheters. Li *et al.* [2012] reported an average error of only 10–15% of the local vessel diameter, which is a very good result.

21.6.5.4 Simulation of the Seldinger Technique

All intravascular interventions described above require an initial maneuver to access an appropriate segment of the vascular tree. The standard approach to get this access is referred to as the *Seldinger technique* [Seldinger, 1953]. With this technique, physicians feel the pulsation of an artery and perform an initial needle puncture. Then, a guide wire is inserted, which requires careful tactile sensations and dexterity [Luboz *et al.*, 2009].

Luboz *et al.* [2009] present a simulation system that enables training of this key procedure of interventional radiology along with guide wire and catheter simulation. This special training system is motivated by the high level of motor skills required to perform the procedure safely.

Database In the phase documented by Luboz *et al.* [2009], already 23 cases were included, representing vascular pathologies such as aortic aneurysms, aortic dissection, arterial stenosis and renal aneurysms.

Evaluation Trainees should virtually treat the vascular pathologies by choosing an entry point, inserting the guide wire and various instruments. All these actions are tracked and monitored for later analysis. Besides subjective feedback from the trainees, the accuracy was analyzed by means of a silicone phantom filled with a viscous fluid. In summary, a combined model of guide wire, catheter and needle as well as vessel deformations with a special haptic device provide substantial support for training vascular interventions.

21.7 SYSTEMS FOR TRAINING OPERATIVE TECHNIQUES

The design and development of e-learning systems to train surgical procedures is a complex endeavor. A careful user and task analysis including an understanding of the context of use is required as input in the early design process (recall § 21.4.1). The simulation to train operative techniques needs to be "part of a wider training course for an end to end training curriculum" [Coles and John, 2010]. In the following, we briefly describe some prominent and long-term efforts in surgical simulator development starting with minimally-invasive surgery (endoscopic surgery, laparoscopic surgery) and later discuss one example of open surgery, namely temporal bone surgery where a bone burr is employed to drill bones, e.g., to create a cavity for a hearing implant.

21.7.1 LAPAROSCOPIC SURGERY

In laparoscopic surgery, only small incisions in the skin are performed. They are employed to insert long and thin tools (a camera to display the situs and surgical instruments). Essential tasks in laparoscopic surgery are:

- port placement,
- suturing,
- knot tying,
- tissue manipulation, and
- camera navigation.

Eye-hand coordination is challenging, since movements of the tool to the left lead to translations on the right and vice versa. Thus, even a surgeon with considerable experience in open surgery needs a lot of training to perform the same surgery in this minimally-invasive manner. Based on these challenges Coles *et al.* [2011] state: "There are more simulators available in laparoscopy than for any other medical speciality." The importance of substantial training is recognized also because of reports of serious complications [Grantcharov *et al.*, 2004].

KISMET A long-term effort on laparoscopic surgery simulation has been carried out at the Research Center of Karlsruhe. Many aspects of real laparoscopic interventions have been carefully modeled in their KISMET (Kinematic Simulation, Monitoring and Off-Line Programming Environment for Telerobotics) system [Kühnapfel *et al.*, 2000]. Anatomical objects are represented as surface models and soft tissue deformation is realized with mass-spring models. Many effects, such as bleeding and coagulation, are faithfully simulated in their system. A special modeling system was developed to generate the underlying geometric and kinematic models. The system has been refined and force feedback was added [Maass *et al.*, 2003]. The system reached a mature state that enabled clinical tests and a significant learning effect could be demonstrated [Lehmann *et al.*, 2005].

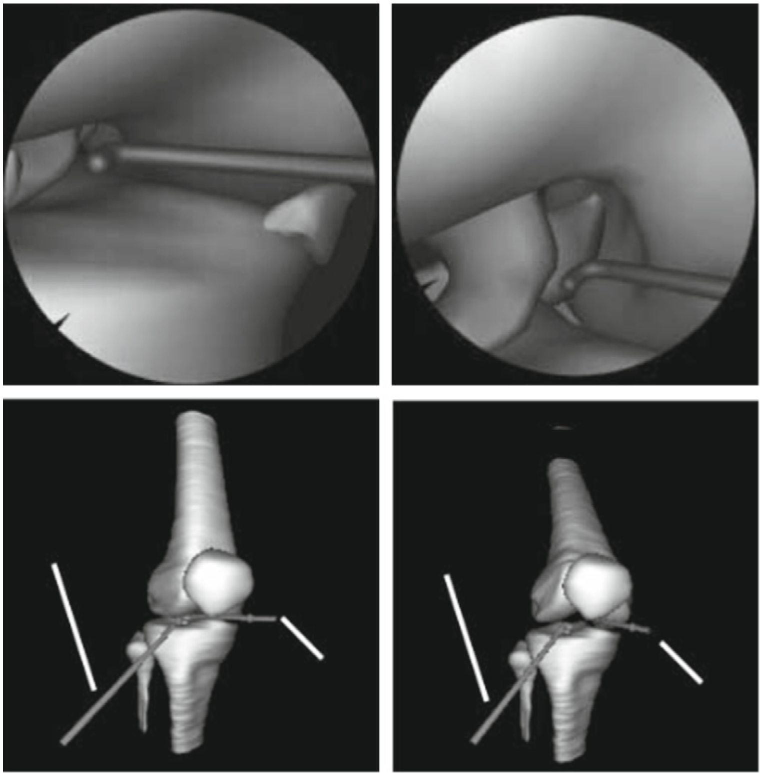

FIGURE e21.35 *Internal (top row) and external (bottom row) views to train arthroscopy (From: [Heng et al., 2004a]).*

Arthroscopic Surgery A special and important example of endoscopic surgery is arthroscopic surgery, i.e., surgical interventions at the knee. There have been a number of dedicate systems for arthroscopy. As an essential example, we describe the system introduced by Heng *et al.* [2004a]. The knee compartments were modeled precisely. Internal and external views are provided to support the understanding of the spatial relations (see Fig. e21.35). Before the actual surgery, an *inspection* is performed and trainees need to learn the navigation in that narrow area.

The knee anatomy contains non-deformable bones and deformable muscles and ligaments. The soft tissue deformation of the deformable objects is constrained by the non-deformable objects that may not be penetrated. The specific FE model is a hybrid combination of an *operational region* and a *non-operational region*. The operational region is the local environment of the pathology where more detail is needed, whereas the more distant non-operational region is modeled in lower detail. Also, topological changes and non-linear deformations are only considered in the operational region.

21.7.2 TEMPORAL BONE SURGERY SIMULATION

Temporal bone surgery (or middle ear surgery) is accomplished primarily in order to attach Cochlea implants as hearing aids and to remove tumors (mastoidectomy) [John *et al.*, 2001]. For this purpose, it is necessary to drill through the mastoid bone (see Fig. e21.36) without hurting relevant structures nearby. Petrous bone surgery involves a surgical site with complex anatomy. Key anatomical features—derived by

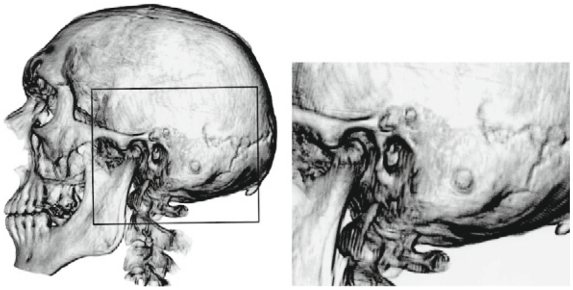

FIGURE e21.36 *Overview of the skull and a closeup view of the mastoid region* (From: [Agus *et al.*, 2003]).

the task analysis—are for example the facial nerve, other neural features, and the jugular bump. The task analysis also provides information related to the most important instruments and materials, as well as to the preferred display type. Three types of instruments are primarily used:

- a *burr* reducing tracebular bone in fine dust,
- an *irrigator* to introduce water, and
- a *sucker* which removes bone dust and water.

Temporal bone surgery is performed by the surgeon holding a high-speed burr in one and a suction device in the other hand. The latter is used to remove the mixing of bone dust with water [John *et al.*, 2001]. The primary learning objectives are to train access to the middle ear and to train the drilling process itself. It is important that all the above-mentioned effects are simulated. Otherwise, important aspects such as the need for regular irrigation and suction are not perceived [Agus *et al.*, 2003].

Learning this type of surgery with conventional training is very expensive, since advanced microsurgical skills need to be acquired. Wiet *et al.* [2011] estimate that a five year period with annual costs of 80.000 is required to gain proficiency.

Virtual temporal bone surgery has attracted much research in the last years. The IERAPS (Integrated Environment for the Rehearsal And Planning of Surgical Intervention) project represents the second large-scale effort to virtual petrous bone surgery [John *et al.*, 2001].

The Ohio Virtual Temporal Bone Simulator was already introduced in [Wiet and Bryan, 2000] and focused on bone removal. Meanwhile it experienced a long development and continuous improvement [Wiet *et al.*, 2011, 2012]. The latest development was based on different data sources. Besides standard CT data, also microCT and ultraCT data were employed with a spatial resolution of 0.06 mm and 0.006 mm, respectively. In particular the display of neural structures benefits from this very high resolution. However, data handling is challenging with the high amount of data involved (500 Gbytes). The Ohio Virtual Temporal Bone simulator was disseminated to eight research institutions, enabling a large validation study with 66 trainees [Wiet *et al.*, 2012]. Besides visual and haptic feedback, also acoustic feedback is provided to convey the sound of the drill (this technique was also used in the VOXEL-MAN temporal bone simulator presented by Zirkle *et al.* [2007]).

Bone removal is accomplished by extending virtual resection techniques described in Chapter 9. Multiresolution approaches such as octrees are essential to effectively localize the voxels which are affected by the movement of the virtual tool. Voxels that are removed become transparent, whereas voxels affected by local bleeding become reddish. While in virtual resection the removal of voxels is just a Boolean operation, in surgery simulation it is necessary to provide adequate force feedback. A physically motivated simulation of the burr/bone interaction is feasible but rather complex, since secondary effects caused by the irrigator and the sucker need to be considered [Agus *et al.*, 2003].

A long-term effort on simulating petrous bone surgery has also been accomplished at the University hospital Hamburg-Eppendorf [Petersik *et al.*, 2002, Pflesser *et al.*, 2002] by the same group that pioneered anatomy education with voxel-based models (recall § 21.3). Among others, they focused on a high-quality visual representation of all relevant anatomical structures. The system employs high-quality volume visualization at subvoxel accuracy and haptic rendering based on a volume representation. The spatial accuracy of the data as well as of the rendering supports the tactile sense of small anatomical structures (e.g., nerves), which is essential for the trainee's learning process. The drill is represented as a sphere-shaped tool, where 26 positions at the sphere's surface are sampled to detect collisions. Soft tissue deformation is not considered, since drilling the temporal bone does not cause significant elastic deformations.

The trainee may choose different kinds of drills or perform drilling while watching the scene displayed in stereoscopic mode. Much effort was spent on mimicking the real situation, in particular with respect to the patient's orientation, the surgeon's viewing direction and hand orientation. The trainees use the stylus of the force feedback device (PHANTOM 1.0 from SENSABLE TECHNOLOGIES), which mimics the drill. They thus get the haptic feeling of the real procedure. Even drilling vibrations and sounds have been faithfully simulated.

21.7.3 WEB-BASED SURGICAL SIMULATORS

As discussed in § 21.2.3, web-based systems strongly improve the accessability and enable widespread use. Of course, a full-fledged surgical simulator cannot be operated just by a mouse and a web browser [John, 2007]. However, low fidelity simulation with simplified geometric models is possible. Even soft tissue deformation may be enabled if a "cheap" solution, such as the ChainMail algorithm, is used [Li and Brodlie, 2003]. Dodd *et al.* [2002] introduced lumbar puncture training with a combination of Java applets and VRML. Even some kind of force feedback is provided by extending VRML with special haptic nodes. The REACHIN interface was employed for this purpose.[14] In the absence of force feedback, collision detection may be used to prevent interpenetration of objects and convey collisions with visual or audio feedback.

21.7.4 COMMERCIAL SURGICAL SIMULATORS

In the following, we give a brief overview on commercial systems to encourage readers to look for more and up-to-date information. The focus of commercial products is minimally-invasive surgery, primarily laparoscopic surgery. The following list of vendors and products is a selective list, that is by no means comprehensive.

SIMBIONIX[15] is a leading provider that offers simulator-based training for minimally-invasive surgery (LAP Mentor for, ARTHRO Mentor for arthroscopy with a knee and shoulder module). The LAP Mentor supports 60 basic tasks and procedures in laparoscopy including suturing and anastomosis exercises and cholecystectomy training. The ARTHRO Mentor supports both diagnostic and therapeutic procedures. As a third example, we mention the ANGIO Mentor that enables the training of endovascular surgery, e.g., for treating diseases of the cerebral vasculature. For all products, several validation studies are documented.

MENTICE[16] is another company that offers several simulation-based training systems. The VIST Lab supports the training of endovascular procedures, including a wide range of interventions, e.g., aortic valve

14 http://www.reachin.se/products/reachinapi/.
15 http://simbionix.com/.
16 http://www.mentice.com/.

implantation, coronary angiography, and renal interventions. Again, the development was added by substantial validation studies. Also a portable variant, VIST-C, is available that may be used for training courses.

SurgicalScience[17] provides basic laparoscopy training with their LapSim system. The basic tasks and procedures are similar to the LAP Mentor. EndoSim, the second major product, provides colonoscopy and bronchoscopy training.

Finally, we mention to the products of Simendo.[18] They offer support for various endoscopic and laparoscopic training procedures and handling special devices for endoscopy.

In general, these high-end systems meanwhile do not rely on general haptic devices but employ modified or completely custom-made instruments to provide a high degree of realism.

21.8 TRAINING SYSTEMS BASED ON PHYSICAL MODELS

All training systems described so far do not operate with real instruments, such as microscopes, ultrasound probes, guide wires, and needles. Even if force feedback is provided, force feedback devices are only loosely related to real instruments. Even the most advanced systems that employ modified haptic devices cannot fully convey the impression of real instruments.

To integrate real instruments and other devices is *one* major motivation for training based on physical models. Another major motivation for training with physical models comes from the shortcomings of training with cadavers. Not only that reports from many countries indicate that there is severe shortage of cadavers [Wiet *et al.*, 2012], but cadavers do not represent the full spectrum of pathologies. As an example, for learning temporal bone surgery, pathologies around the inner and middle ear are crucial. Cadavers rarely exhibit such pathologies. The large-scale use of animals for training has also severe problems, among them ethical problems.

Finally, touching, moving and rotating a geometric model of anatomical and pathological structures is just perceived as more realistic and supports a collaborative discussion between two trainees. Abdel-Sayed and von Segesser [2011] summarize the potential of rapid prototyping for procedural training in cardiovascular surgery as follows:

1. better identification of structural abnormalities, e.g., complex congenital heart failures,
2. more reliable identification of the best surgical strategy, and
3. improved surgical skills by a realistic training setting.

These statements—despite being related to cardiovascular surgery—can be largely generalized to many interventional and surgical procedures.

Although procedural training is the most essential application for physical models, Thomas *et al.* [2010] convincingly demonstrated that it may also be used for anatomy education when virtual information is overlaid with physical information (recall Chap. 18 where we discussed such *augmented reality* solutions primarily for surgery).

In the following, we describe the generation of physical models from medical image data and present selected examples of the use of such systems for training. Furthermore, we describe the basic technology and two selected applications in surgery training.

17 http://www.surgical-science.com/.
18 http://www.simendo.eu/.

21.8.1 GEOMETRIC MODELING AND RAPID PROTOTYPING

The potential of rapid prototyping for surgical training was recognized early. Begall and Vorwerk [1998] suggested to use physical models for the training of temporal bone surgery. Widespread use, however, was not possible at that time. In recent years, rapid prototyping technology developed at a rapid pace and now allows to create larger models, models with different materials and colors, even with semi-transparent materials. Last but not least, the acquisition of rapid prototyping technology and the price to use it decreased considerably. The term "rapid" is somewhat debatable—the process lasts a couple of hours. Knox *et al.* [2005] comment this ironically: "The word rapid …uses an industrial rather than a medical timescale." While this is a serious argument for the use in clinical routine, for medical training the duration of fabrication is no serious counter-argument.

Thus, instead of using cadavers, physical models may be created with rapid prototyping (also referred to as stereolithography). These physical models may be easily replicated ensuring reproducibility of the training experience and supporting skills assessment. As an example, Figure e21.37 shows a physical model of the skull attached with various microcontrollers that are employed to detect injuries during surgical training, e.g., drill procedures at the lateral skull. Besides various advantages of the training with physical models, a common problem is that *physiology* can hardly be realized [Coles *et al.*, 2011].

Rapid Prototyping Technology The actual rapid prototyping process is also challenging and involves the choice of the technology, device and materials. There are different rapid prototyping technologies, such as stereolithography and laser sintering. Silicone is a frequently used material. Abdel-Sayed and von Segesser [2011] give an overview on techniques and materials. There are various vendors of rapid prototyping machines, e.g., Z CORPORATION with the series of ZPrinter 150–850.[19] In particular, with cheaper 3D printers it might be necessary to smoothen the result slightly. Choi *et al.* [2002] describe artifacts from rapid prototyping. Basically, the physical objects are created by milling away unwanted parts of a solid block by or building up the model in an accretion process.

Creating Vascular Models Knox *et al.* [2005] describe the use of rapid prototyping for creating vascular models for teaching. They created accurate models of a carotid stenosis and of a basilar tip aneurysm. Lermusiaux *et al.* [2001] also discussed the fabrication of vascular surface models. In their particular case, aortic aneurysms were created in their original size. Smaller problems occur in the reproduction

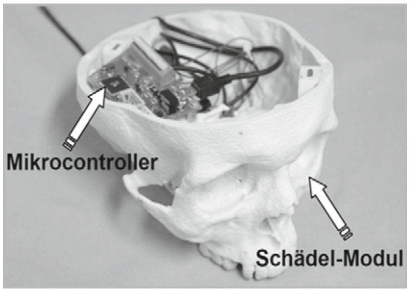

FIGURE e21.37 *Physical models attached with electronic devices enable reliable assessment of trainees' performance in a training session (Courtesy of Werner Korb, University of Applied Sciences, Leipzig).*

19 http://www.zcorp.com.

of complex anatomical structures, such as vasculature. Knox *et al.* [2005] discuss that upper surfaces of vascular structures are more faithfully represented than lower surfaces. Choi *et al.* [2002] discuss limitations of accuracy in creating physical models of anatomical structures. However, in summary, rapid prototyping has developed into a feasible method that produces accurate models, and with an advanced 3D printer also a substantial flexibility is available.

Geometric Modeling Why are physical models relevant in a chapter on computer-assisted medical education? The physical models are based on geometric models that are primarily created from patient data, such as CT and MRI. Thus, image segmentation and surface extraction are crucial.

Even for the use of geometric models in a virtual environment, surface models are often carefully post-processed, e.g., with smoothing or remeshing (recall). For rapid prototyping, *modeling* plays an even more important role. Very thin structures cannot be physically built. Structures that are too close to each other, are merged in a physical model, an occurrence that should be avoided by an appropriate modification.

Also Blender[20] and 3DS Max[21] possess 3D modeling functionality, enabling the deformation of a model, in order to remove bulges and perform other modifications. However, as professional tools they exhibit quite complex user interfaces. Often, the necessary processing steps can also be performed with Sculptris,[22] a much simpler tool that enables dilation, extrusion, and smoothing. Such operations are performed intuitively by moving corresponding tools over the surface. Often, before but also after such modifications, some kind of *mesh repair* is necessary, e.g., to remove holes or to ensure a good triangle quality. An advanced tool to support these tasks is MeshLab.[23] Users have fine-grained control over the vertices and faces to which such operations are performed. To illustrate the modeling tasks, Figure e21.38 shows how a vascular model is adapted, e.g., for use in a simulator of vascular interventions.

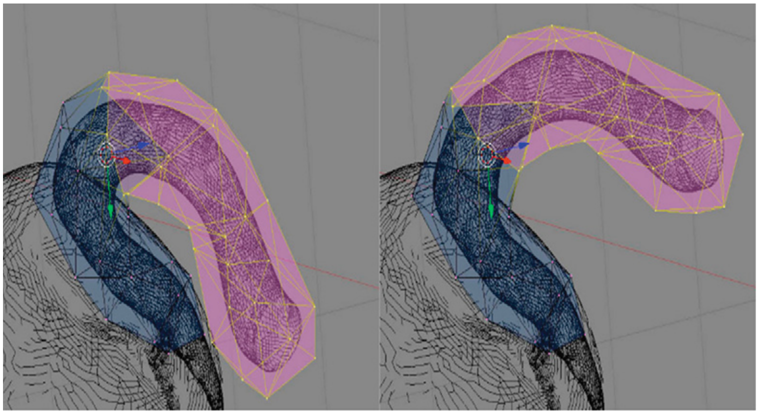

FIGURE e21.38 *Blender is employed to deform a branch of a vascular structure that is too close to another one. The deformation is performed by means of the visual hull (left) and the transformation is propagated to all vertices and edges in the relevant region (Courtesy of Tobias Mönch, University of Magdeburg).*

20 http://www.blender.org/.
21 http://usa.autodesk.com/3ds-max/.
22 http://www.sculptris.com/.
23 http://meshlab.sourceforge.net/.

An alternative to polygon modeling tools are those that operate at the voxel level, such as FreeForm. Geomagic FreeForm[24] is operated with a haptic input device to provide intuitive modeling. While most training systems based on rapid prototyping do not provide self-assessment tools and tools to analyze the trainees' performance, the following two subsections present advanced systems that were equipped with opto-electrical cables and sensors to provide this kind of feedback.

21.8.2 TEMPORAL BONE SURGERY

As we have discussed in § 21.7.2, temporal bone surgery is a particularly challenging surgical task due to the high density of small but crucial anatomical structures. Therefore, a high demand for simulation but also for training with physical models exists, motivating also the pioneering work of Begall and Vorwerk [1998].

Later different attempts have been made to provide a feasible training system based on rapid prototyping technology, e.g., [Suzuki *et al.*, 2004]. We describe the comprehensive training system introduced by Straušs *et al.* [2009]. Its design is based on substantial didactic considerations. These relate to different aspects of dexterity in temporal bone surgery, the complementary mental models of spatial relations as well as to typical learning curves that are characterized by two stages with rapid progress. The initial steep learning curve should be accomplished without access to patients. After a later plateau, there is a second significant increase in performance and avoidance of complications that requires real surgery. Based on these considerations, a list of requirements was defined. Besides some obvious requirements related to ease-of-use, cost effectiveness, and realism of the following requirements are crucial:

- The results of training need to be assessed quantitatively to provide feedback and in order to judge whether this training stage can be finished.
- The training should trigger a moderate level of stress, a so-called *positive stress*. It is expected that this stress level is only achieved if trainees perceive that they control the training effectively.

System Design The training system introduced by Straušs *et al.* [2009] is based on physical models, incorporating the skeletal structures, but also essential risk structures, such as the Nervus facialis, the internal carotid artery and the ossicle chain (see Fig. e21.39, left). Gypsum powder and a bonding agent are used to create the physical model where the risk structures are represented as canals. After initial feedback, the physical models were refined with respect to the use of colors, the representation of some anatomical details and the hardness degree of the canal for the N. facialis. The target anatomy is embedded in a complete model of the skull (see Fig. e21.39, right) to provide a realistic context and enable better handling (the whole target anatomy is rather small). Of course, after a training session the skull model may be reused and only the temporal bone needs to be generated again. In a very similar way, Abdel-Sayed and von Segesser [2011] describe how a model of the heart is inserted in a much larger thorax model.

Trainees used an OR microscope, aspirators and milling machines like in real surgery. The structures at risk are equipped with detectors and fiberoptic cables to detect injuries and assess their severity.

System Evaluation The training system was used by eight experienced surgeons and eight novices and the results were compared with a second group of trainees that employed human cadavers. The evaluation was based on log files and automatically determined injuries, questionnaires completed by the trainees and an assessment of the surgery by an expert with respect to completeness of surgery and injuries. Selected results of this evaluation are:

24 http://geomagic.com/en/products/freeform/overview.

FIGURE e21.39 **Left:** *With an OR microscope realistic surgery training may be performed with a physical model of the temporal bone.* **Right:** *The temporal bone model that is consumed in the training activity is embedded in a reusable skull model (Courtesy of Gero Strauß, IRDC Leipzig).*

- The visual and haptic realism of training with physical models was assessed as very high (1.8 on a scale from −2 to 2, with 2 representing the highest degree of realism). This is an even a better assessment of this group than the assessment related to the training with cadavers, probably because the soft tissue structures in cadavers strongly differ from living tissue.
- Also the injuries happening during training were considered as very realistic (1.6 at the same scale).
- Experts caused less injuries and in particular injuries of lower severity, e.g., injuries of the N. facialis.

Based on the prototype described in Straušs *et al.* [2009], a commercial product was created and regularly used for training courses. Similar model creation processes were designed to support sinus and skull base surgery.[25]

21.8.3 TRAINING OF SPINE SURGERY

Korb *et al.* [2011] describe an advanced mechatronic system based on physical models for training spine surgery in the lumbar spine segments. They carefully investigated a large variety of materials in order to select a combination that provides very good haptical realism. Synthetic and organic materials, e.g., polyurethane and variants of gelatin) were assessed systematically by anatomists and neurosurgeons. A manufacturing process was designed and refined to produce all necessary materials reliably and efficiently. The modeling tasks were performed with FreeForm. The system design was based on many visits to the OR with a focus on neurosurgical interventions on the spine.

Figure e21.40 shows an example of a physical model used for spine surgery training. The system also contains an artificial blood pump. The liquid used for this pump resembles blood in its appearance as well as in major biomechanical properties, e.g., viscosity. Thus, when the trainee damages certain anatomical structures in the model, a realistic bleeding is simulated.

The whole system was evaluated by eleven surgeons primarily with respect to optical and haptic realism. Vertebra and prolapse as well as the dura were considered as realistic by the majority of the test persons.

25 www.phacon-leipzig.de/.

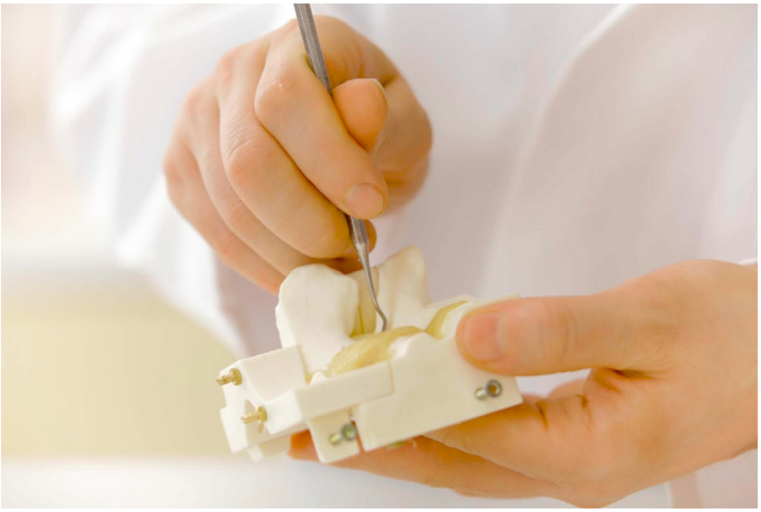

FIGURE e21.40 *A physical model of a vertebra with various materials representing different levels of stiffness and elasticity was created with rapid prototyping (Courtesy of Werner Korb, University of Applied Sciences, Leipzig).*

21.9 SKILLS ASSESSMENT

Once surgical simulators are designed, developed, and refined after gathering initial feedback from the first users, skills assessment becomes an important issue. Surgical simulators should enable

- a substantial learning effect, and
- a learning effect that can be transferred to real surgery.

In particular commercial systems put emphasis on skills assessment, since a proven benefit is essential for marketing. While this is not our motivation here, skills assessment is primarily important to ensure that surgical and interventional training finds its way in clinical routine and actually improves clinical care. An essential question is which tasks should be used to assess and certify the acquired skills. This selection benefits from a careful cognitive task analysis, including decision points (recall § 21.4.1 and [Johnson *et al.*, 2006].

21.9.1 IMPORTANT TERMS

There are some frequently used terms discussed in the validation of surgical simulators that will be defined in the following:

Definition 21.1. **Face validity** is a general term that summarizes *subjective assessments* whether a test or simulation seems to actually measure what it is supposed to measure.

If the face validity of a simulator is low, users do not take the corresponding training seriously. As an example, force feedback devices with a syringe-shaped end effector tend to have a higher face validity than general force feedback devices when used for training needle-based interventions. Thus, trainees and experts *believe* that the training is realistic and that the acquired skills may be transferred to clinical practice. Face validity is verified with expert reviews and questionnaires.

Definition 21.2. **Concurrent validity** is a term that characterizes the ability of a simulator to compare the trainees' performances with a gold standard.

The gold standard may be another (already carefully assessed simulator), mechanical or cadaver training. If the training results of trainees have a similar tendency like in the gold standard, this further increases trust in a simulator.

Definition 21.3. **Construct validity** is a general psychological term. Translated to surgery simulator, construct validity refers to the validity of inferences that observations and measurements derived from a simulator actually characterize surgical skills.

A high construct validity is usually assumed when novices and experienced users differ significantly in their results (error rates, task completion times, ...) within a simulator such that the higher experience of experts leads to better results [Oropesa *et al.*, 2010]. With a high construct validity, measures are expected to be reliable and reproducible. It is more difficult to ensure construct validity compared to face validity.

A widely used term in skills assessment is also *content validity*, that is related to the question whether the material provided in the training is realistic and sufficiently variable. Finally, *predictive validity* is the term that characterizes the degree to which success in a training simulator can be transferred to clinical practice. Thus, a high predictive validity is the ultimate goal of a training system.

Frameworks for Skill Assessment have been developed that are relevant and inspiring for surgery simulation [Oropesa *et al.*, 2010]. The *Objective Structured Clinical Examination* (OSCE) was introduced in the 1970s to assess the trainees' performance at various clinical stations manually but in a reproducible manner (using standardized checklists). The OSCE also incorporates technical skills assessment but only as a minor aspect. This lead to the introduction of the *Objective Structured Assessment of Technical Skills* (OSATS) in the 1990s focusing on procedural knowledge. Minimally-invasive surgery has a number of unique aspects not reflected in OSATS. Again a refined assessment framework was developed: the *Global Assessment of Laparoscopic Skills* (GOALS). This assessment framework is not bound to any particular kind of training (cadaver, mechanical, virtual reality), which enables to use it to compare the efficiency of different training systems. For more details on the application of these frameworks, see Fried and Feldman [2008].

For other kinds of surgery, e.g., in otolaryngology, but also for interventional radiology, there is no such reliable, practical, and standardized skills assessment [Wiet *et al.*, 2012].

21.9.2 AUTOMATIC SKILLS ASSESSMENT

When the trainees' actions are consequently monitored, an automatic skills assessment is possible. This is highly desirable due to the large effort and subjective variability of manual skills assessment by experts.

A relevant parameter is the time required to solve tasks with the simulator assuming that experts make less erroneous or unnecessary movements and are faster. For some procedures, it is questionable that trainees should aim for speed, e.g., in complex intervascular procedures, where slow and careful working might be more desirable compared to fast working with high risk. However, almost all automatic skills assessment tools consider time an essential parameter.

Most other parameters are either related to hand movement or to tool-tissue interactions. Hand movement may be assessed with respect to smoothness and other parameters derived from a speed profile. Tool-tissue interactions may be characterized by the forces that are applied to the tissue [Oropesa *et al.*, 2010]. The opto-electronic devices attached to a physical model shown in Figure e21.41 are used to

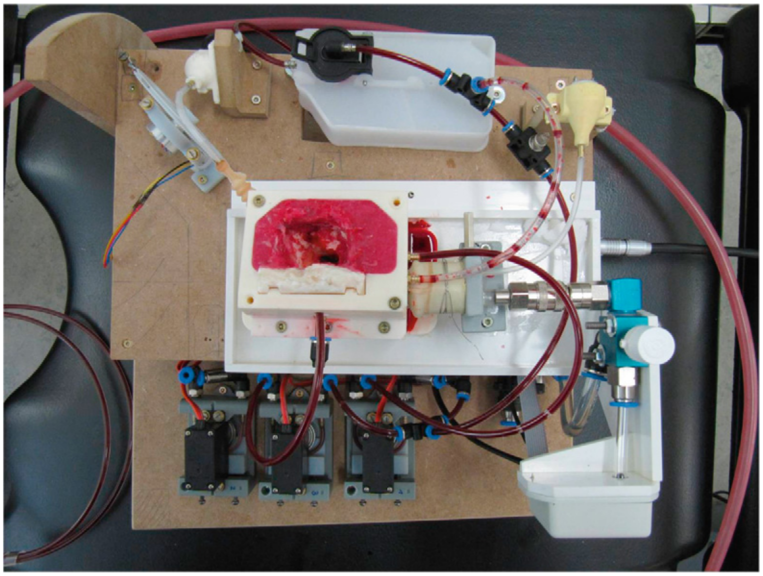

FIGURE e21.41 *A complex setup with physical model, blood pump and various sensors enables realistic training of spine surgery with automatic skills assessment (Courtesy of Werner Korb, University of Applied Sciences, Leipzig).*

determine such measures. Tissue damage, dangerous movements, economy of movements may also be detected and are frequently employed for automatic skills assessment [Wiet *et al.*, 2012].

The specific role of one particular force- or movement-related parameter to a relevant surgical skill is only partially understood so far. Thus, more research is necessary to ensure construct and predictive validity of such measures.

In the following, we briefly describe selected studies to give examples for viable and reliable methods of validation.

21.9.3 SKILLS ASSESSMENT STUDIES

One of the earliest validation studies relates to the minimally-invasive VR simulator for laparoscopic surgery (MIST VR) [Taffinder *et al.*, 1998]. They defined a score for various aspects of psychomotor skill and conducted two studies related to the simulator: the first study assesses surgeons of different surgical experience to validate the scoring system and the second study investigates the effect of a standard laparoscopic surgery training course. Experienced surgeons (more than 100 laparoscopic cholecystectomies) were significantly more efficient, made less correctional submovements and completed the tasks faster than trainee surgeons. Thus, the *construct validity* was high. The training course caused an improvement in efficiency and a reduction in errors for trainee surgeons.

Another study also related to the MIST VR simulator was presented by Grantcharov *et al.* [2004]. This randomized clinical trial is recognized as a high-quality study [Oropesa *et al.*, 2010], since rigorous statistical analysis was performed and confounding variables likely to cause bias carefully avoided. In a randomized manner, ten trainees were assigned to a virtual reality training group and ten received no training. Training consisted of ten repetitions of six basic tasks relevant in laparoscopic surgery. A final cholecystectomy of all 20 trainees was analyzed by two independent observers. Training improved operation time, economy of movement and error rate in a significant manner.

Sutherland *et al.* [2006] provided a comprehensive analysis of randomized controlled trials to assess the acquired skills with various forms of surgical training available at that time. These studies lead to contradictory results even for similar procedures. The survey indicates how difficult it is to perform and compare studies. The background knowledge of the trainees, the time of training and the specific tasks are among the confounding factors that make comparisons challenging. In essence, the studies showed a significant training effect by simulator training (compared to no training), but no significant advantage of either mechanical or virtual reality-based training.

Oropesa *et al.* [2010] give an overview on more recent skills assessment and validation studies applied to commercial surgical simulators. Some 30 studies are mentioned that were focused on either face, content, construct, concurrent, or predictive validity. Basically all commercial simulators, mentioned in § 21.7.4, were subject to such studies.

The Ohio Temporal Bone Simulator was also subject to a validation study. In a multiinstitutional study with 66 trainees a significant effect of the simulator training could be demonstrated [Wiet *et al.*, 2012]. Compared to cadaver training, the effect of simulator training was not significantly different, which is a good result at second glance due to the shortage of cadavers and the automatic skill assessment only possible with the simulator.

Discussion Despite the efforts to create and refine advanced surgery simulators, these are rarely integrated into the medical curriculum. The integration with other modes of learning is essential for a widespread use of surgery simulators. There are some encouraging examples. The minimally-invasive virtual reality simulator (MIST VR) was used for a *competency-based training curriculum*—a structured virtual reality training program aimed at achieving previously defined competency levels [Aggarwal *et al.*, 2006].

21.10 SUMMARY

In this chapter, we described educational systems and the visualization techniques and strategies which characterize them. Educational systems are based on high-quality datasets, reliable segmentation results, and symbolic knowledge bases carefully linked to the corresponding portions of medical volume data. Although many technical problems have been solved, computer support still plays a minor role in medical education. It is necessary to fine-tune educational systems to the relevant learning objectives, to create stimulating experiences using these systems and to increase the awareness of instructors. Training systems still need to be better integrated into traditional courses and curricula.

Outlook Despite the success of anatomy education systems much work lies ahead. Educational systems in general are based on only one level of spatial resolution—usually the resolution of medical image data. The incorporation of higher resolution medical image data (MicroCT and microscopic data), the development of interaction facilities to explore data at different levels are two of the remaining challenges.

Advanced visual support and computer-assisted training in operative disciplines still often focus on low-level technical problems primarily related to haptic and visual realism. A particular limitation is the focus on single organs. Whole body parts are not considered due to the associated complexity of modeling systems of organs.

Moreover, real surgery is a team effort, involving several physicians (including anesthesia specialists) and support staff. Collaborative training, e.g., in order to handle critical incidents, is a challenge for future training systems. Finally, surgery simulators today do not consider functional aspects. In the future, physiologic modeling of organic systems, such as cardiovascular and digestive systems, will be included in surgery simulation.

A promising area for future work aiming at improved acceptance is the use of game technology and concepts, such as structuring training in appropriate levels, computing scores, providing bonus points, etc. As an example Qin *et al.* [2010] present a system where orthopedic surgery training is enhanced by such concepts. The particular learning goal is to improve blood management—an essential aspect since severe blood loss is a major complication of orthopedic surgery. Also Chan *et al.* [2010] employ gaming concepts for improving biopsy needle placement. From a practical point of view, computer-assisted training systems, in particular the high-end simulators, are just very expensive. Among others, more efficient content generation is necessary to develop solutions at more affordable prices.

FURTHER READING

A simulator for hepatic surgery was developed at INRIA, primarily to train laparoscopic interventions [Cotin *et al.*, 2000a, Delingette and Ayache, 2005]. We have not carefully discussed tool-tissue interactions in surgery simulation. For an overview, see Misra *et al.* [2008]. A valuable source of information concerning biomechanical properties of human tissue is the book [Humphrey, 2004].

Surgery simulation in a simplified manner may also be performed with the ChainMail algorithm [Gibson, 1997, Li and Brodlie, 2003].

With respect to the surgical simulation, we want to point to the MISTELS system (McGill Inanimate System for Training and evaluation of Laparoscopic Skills). A series of publications describes its development, its use and its validation with respect to the ability to assess surgical skills reliably [Derossis *et al.*, 1998, Dauster *et al.*, 2005, Feldman *et al.*, 2004].

Our discussion of training systems for needle-based interventions is by far not complete. Other notable developments were carried out at the National University of Singapore for percutaneous vertebroplasty (using a glove from Cyber Grasp and a Delta haptic device [Chui *et al.*, 2006] and at the Centre for Advanced Studies, Italy, where a trainer for catheter insertion was accomplished). This trainer used a head-tracked stereoscopic viewing system [Zorcolo *et al.*, 1999]. A system for training Chinese acupuncture was presented by Heng *et al.* [2004b]. Later Heng *et al.* [2006] also described specific visco-elastic models for muscles and adipose tissue to simulate needle penetration. Tavakoli *et al.* [2006] provide an in-depth discussion of haptic interaction issues for endoscopic surgery training. As a more general hint for thinking about haptics, the work of Formaglio *et al.* [2008] is recommended. They discuss ergonomic problems, particularly fatigue effects, of current force feedback devices and discuss research attempts toward a device that may be released and remain at their previous position, similar to the mouse at the desktop.

Due to its high importance, we discussed spine surgery training at various stages of the chapter. Readers interested in this area are also directed to Ra *et al.* [2002].